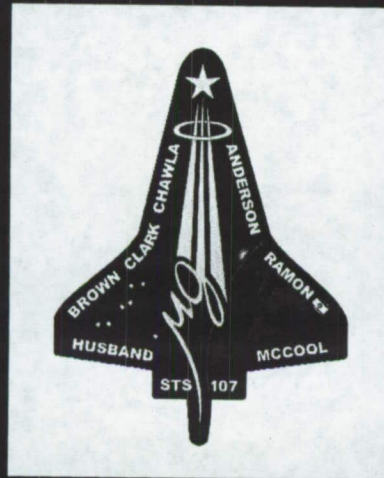


The Space Shuttle Columbia Accident Investigation: Forensic Tools, Techniques, and Results



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Thomas E. Collins (Boeing-Huntington Beach)
Dr. Gregory A. Jerman (NASA-Marshall Space Flight Center)
Steven J. McDanels (NASA-Kennedy Space Center)
Dr. Robert S. Piascik (NASA-Langley Research Center)
Richard W. Russell (Boeing-Kennedy Space Center)
Dr. Sandeep R. Shah (NASA-Marshall Space Flight Center)**

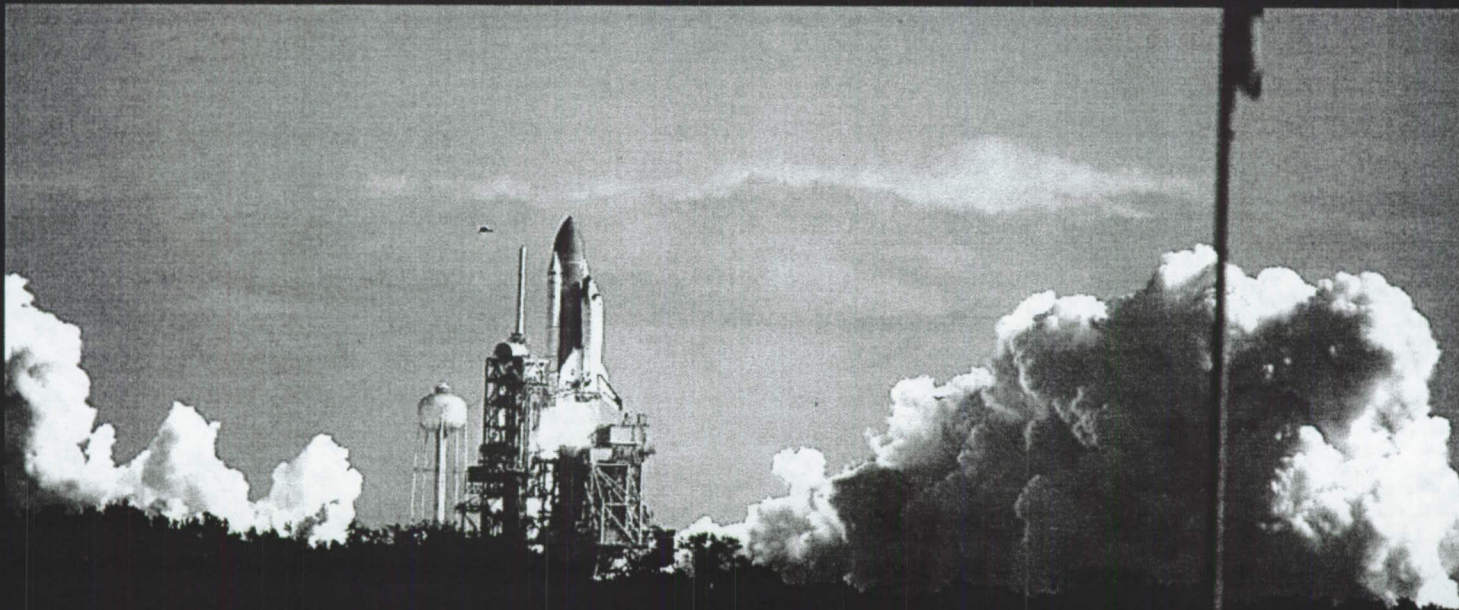
Columbia STS-107



Shuttle Columbia: April 12, 1981

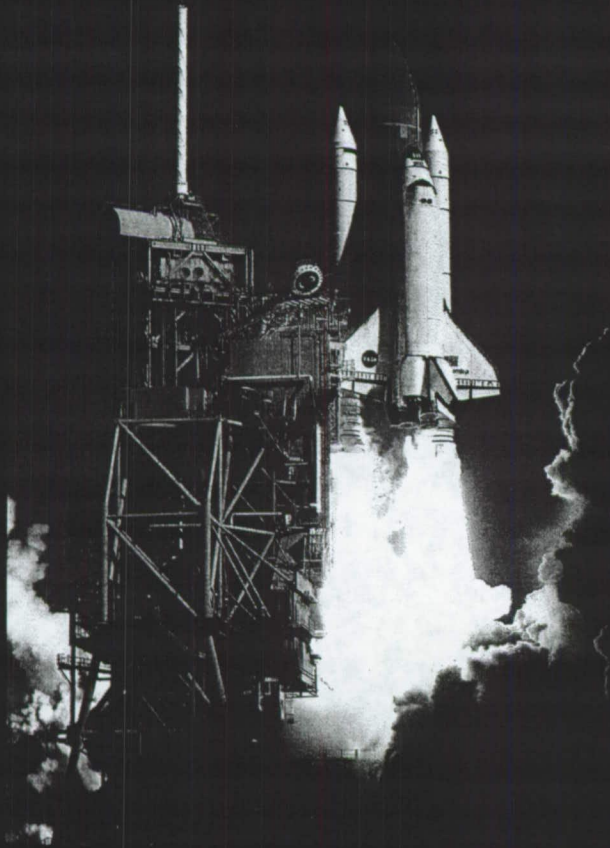


Shuttle Columbia: January 16, 2003

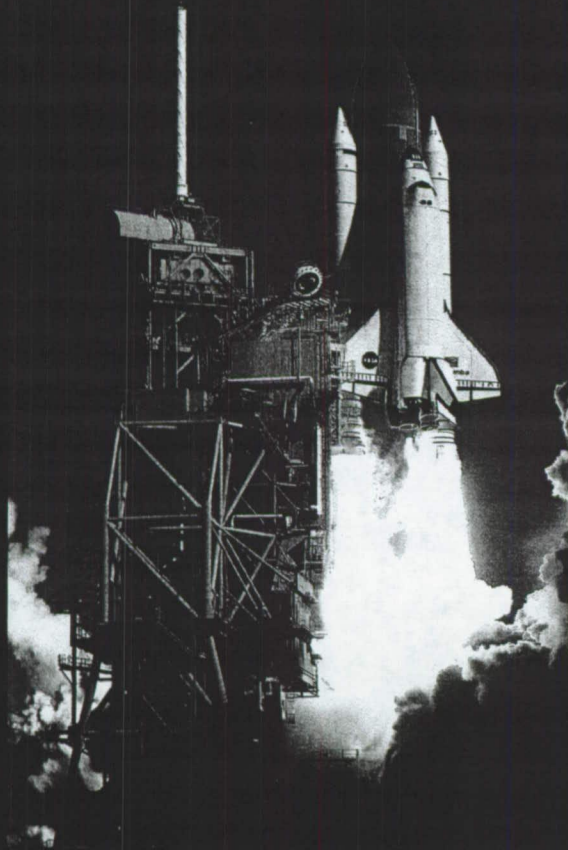


Shuttle Columbia: STS-107

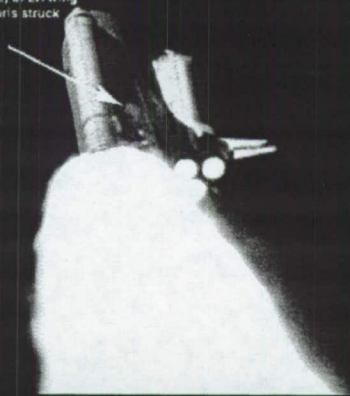
•Launch – January 16, 2003



Shuttle Columbia: STS-107

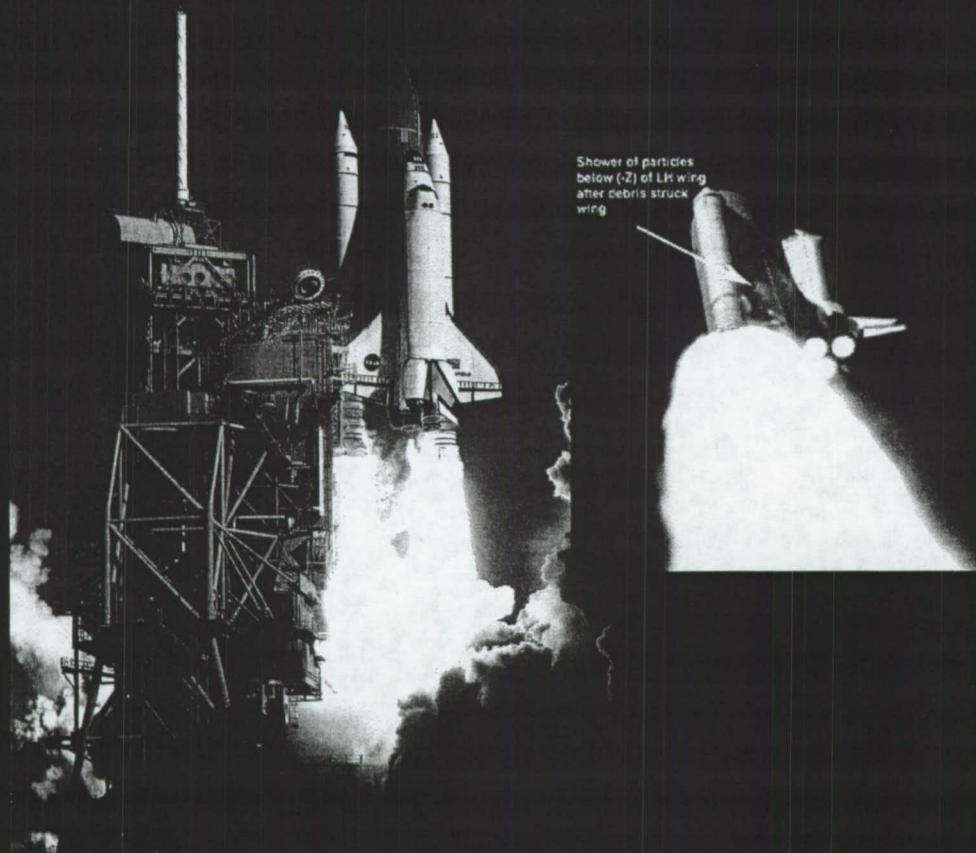


Shower of particles
below (-Z) of LH wing
after debris struck
wing



- Launch – January 16, 2003
- Launch + 81.9 seconds, External Tank left bipod foam strikes Columbia's left wing

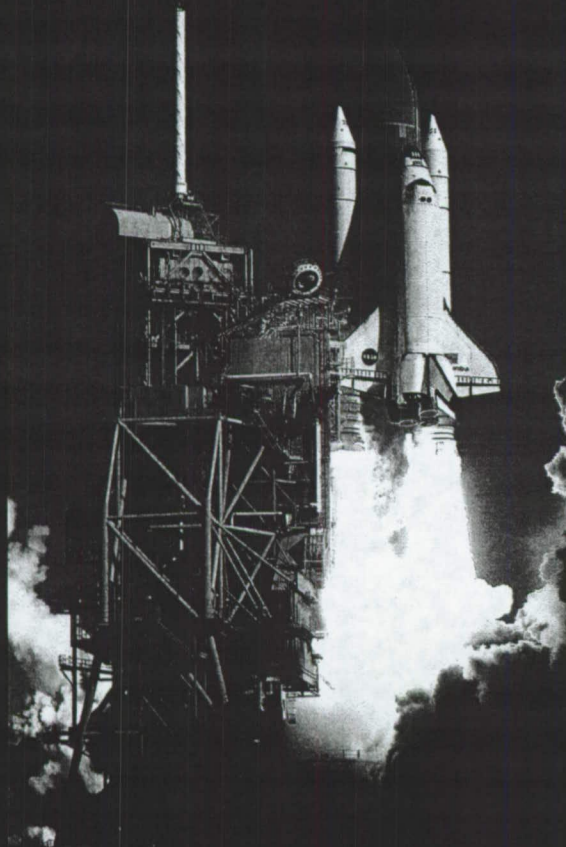
Shuttle Columbia: STS-107



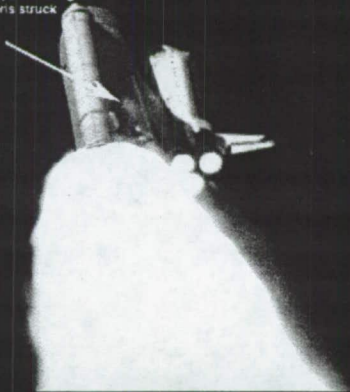
Shower of particles
below (-Z) of Lft wing
after debris struck
wing

- Launch – January 16, 2003
- Launch + 81.9 seconds, External Tank left bipod foam strikes Columbia's left wing
- Approximately 1 minute 24 seconds into peak heating region of re-entry interface, 8:52:17, an off-nominal temperature in the left main landing gear brake line sensor
- Over California first signs of debris shedding observed at 8:53:46 am
- First sign of trouble reported in mission control, at 8:54:24 when four hydraulic sensors were indicating "off-scale low".
- Loss of signal from Columbia recorded at 8:59:32 am.

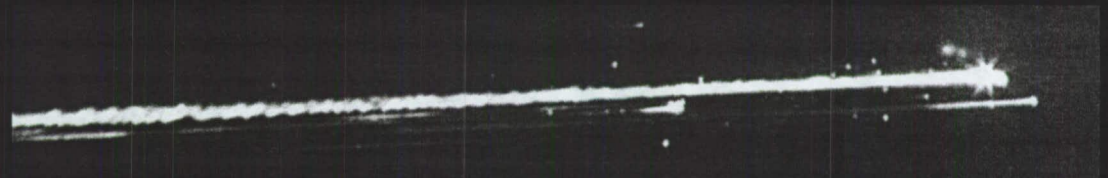
Shuttle Columbia: STS-107



Shower of particles
below (Z) of LK wing
after debris struck
wing

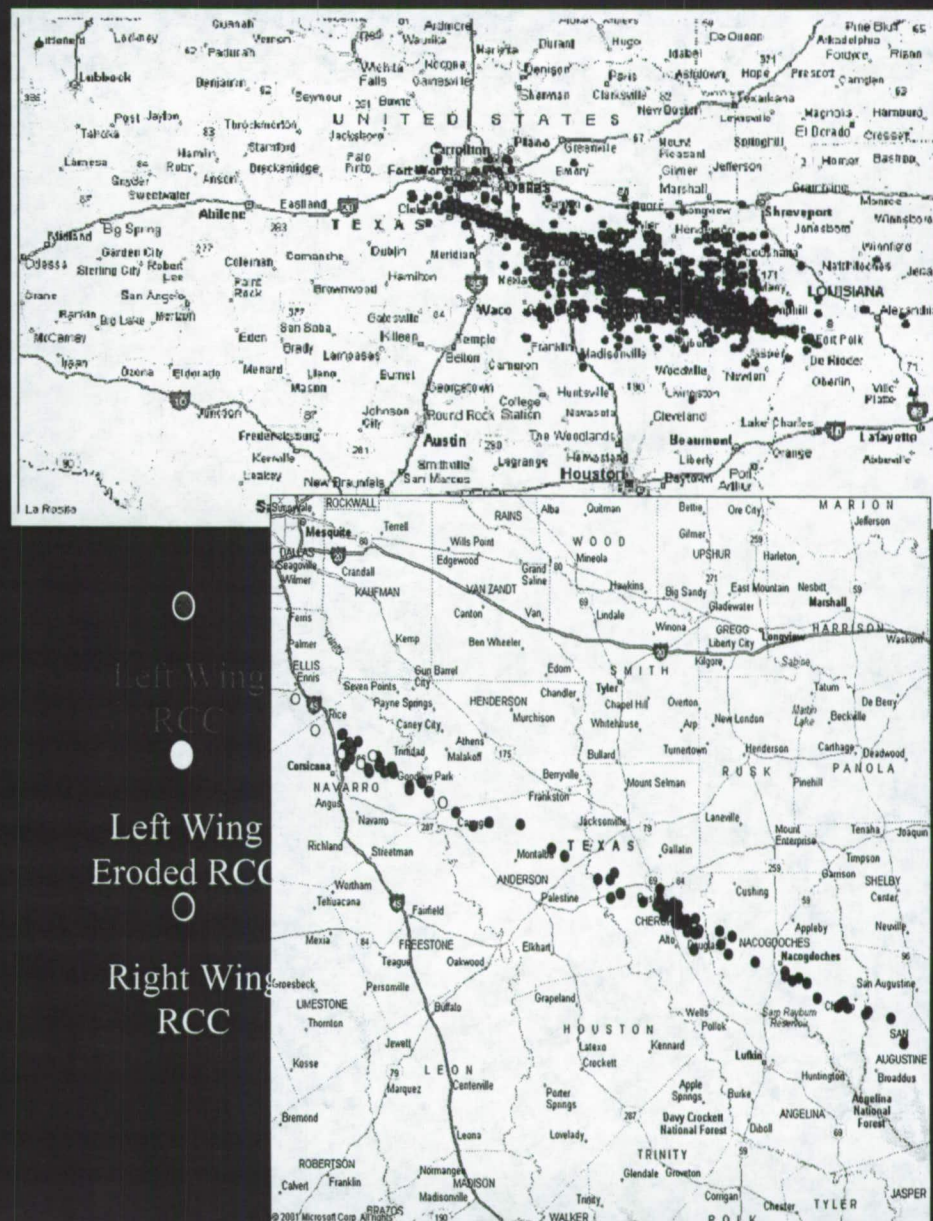


- Launch – January 16, 2003
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- Over California first signs of debris shedding observed at 8:53:46 am
- First sign of trouble reported in mission control, at 8:54:24 when four hydraulic sensors were indicating "off-scale low".
- Loss of signal from Columbia recorded at 8:59:32 am.
- Videos made by observers on the ground at 9:00:18 am revealed that the Orbiter was disintegrating



Recovery

- Mach 18 at an altitude of 208,000 feet at time of break-up
- The size of the debris field was 645 miles long and 10 miles wide
- Each piece of debris was photographed, analyzed for potential hazards, given a unique identification
- Each piece's location was noted and a preliminary identification was attempted
- Debris sent to one of several staging locations, then to the Kennedy Space Center



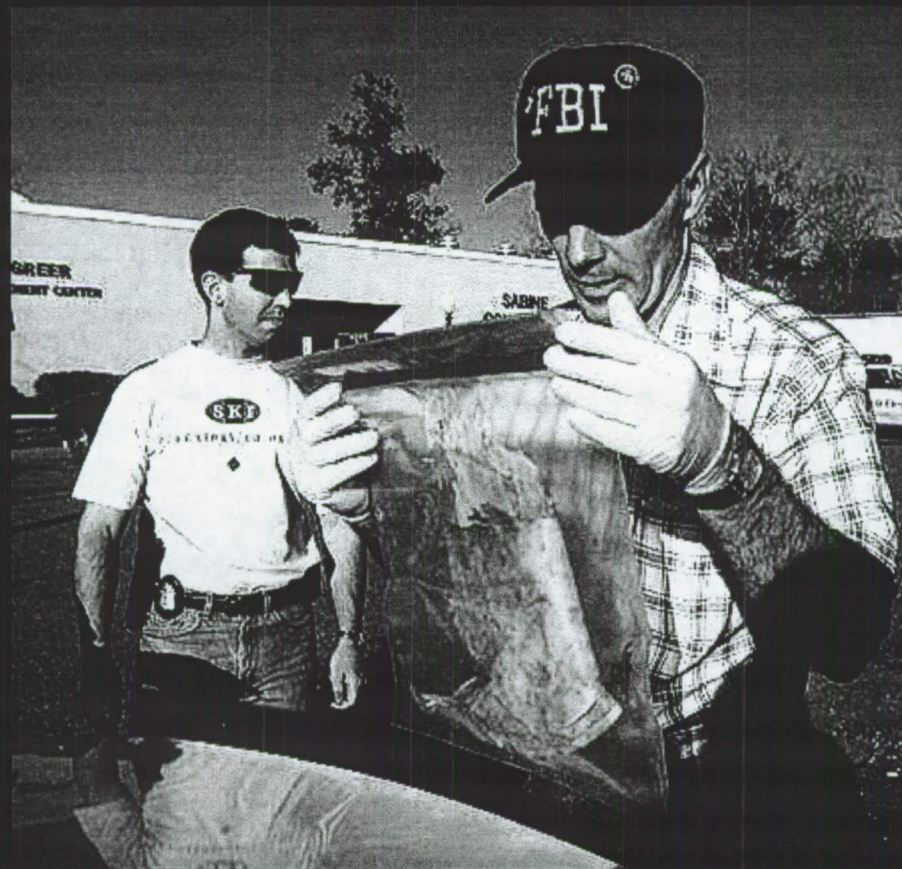
Recovery



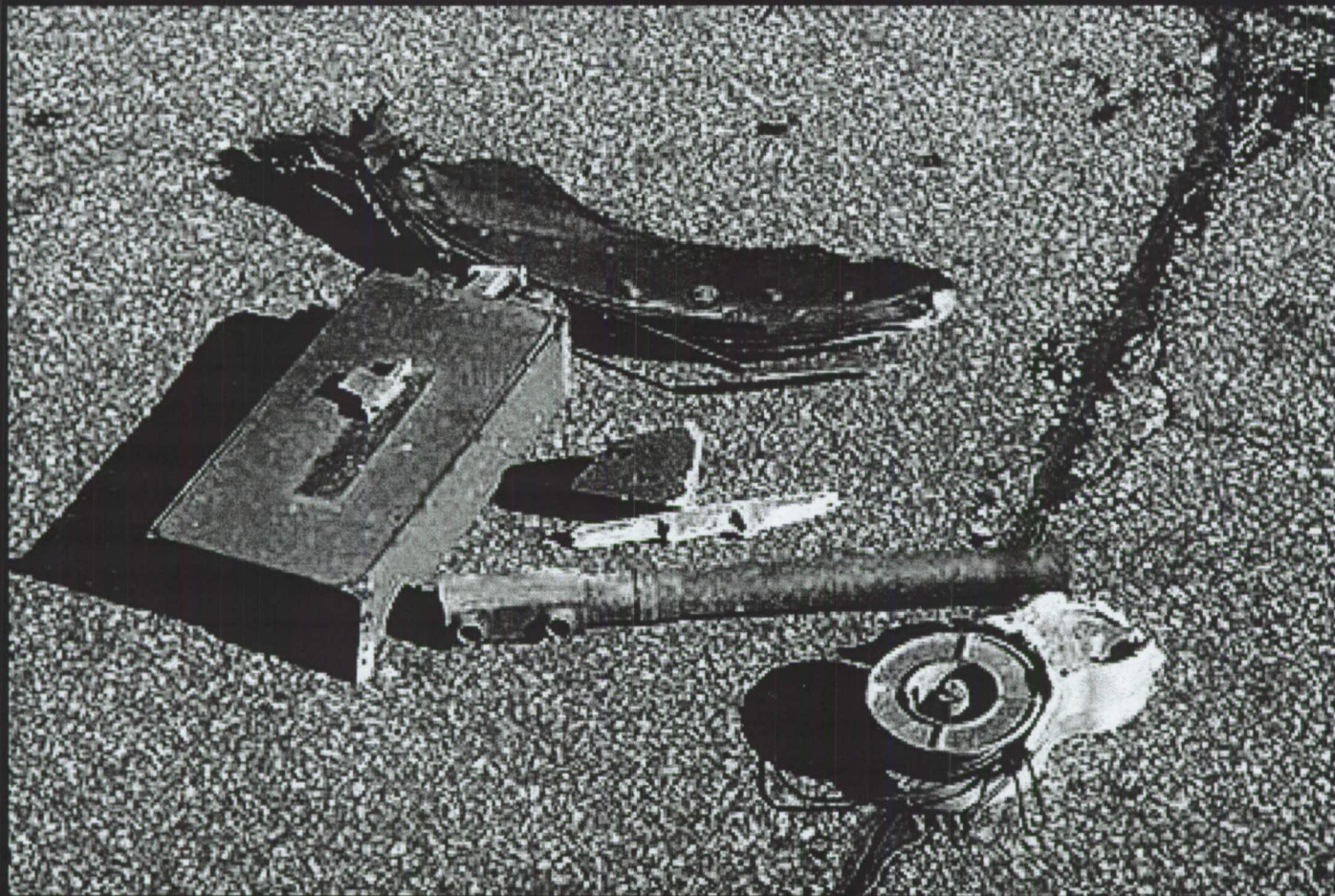
Recovery



Recovery



Recovery



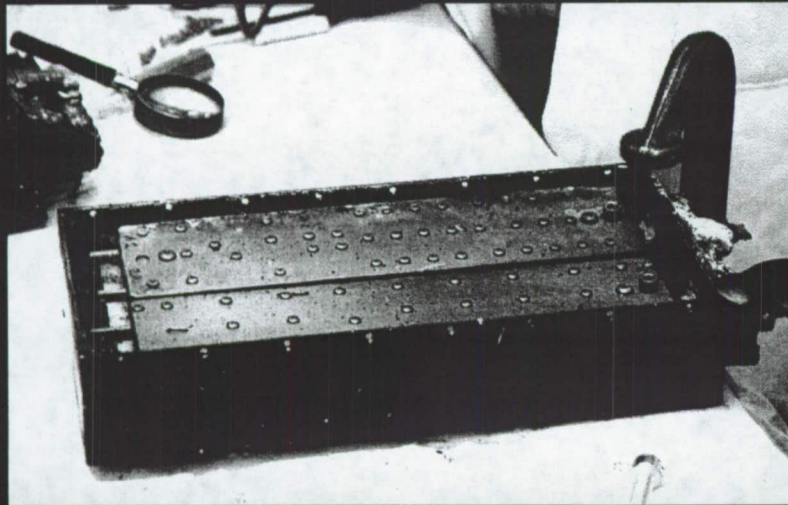
Reconstruction



Reconstruction



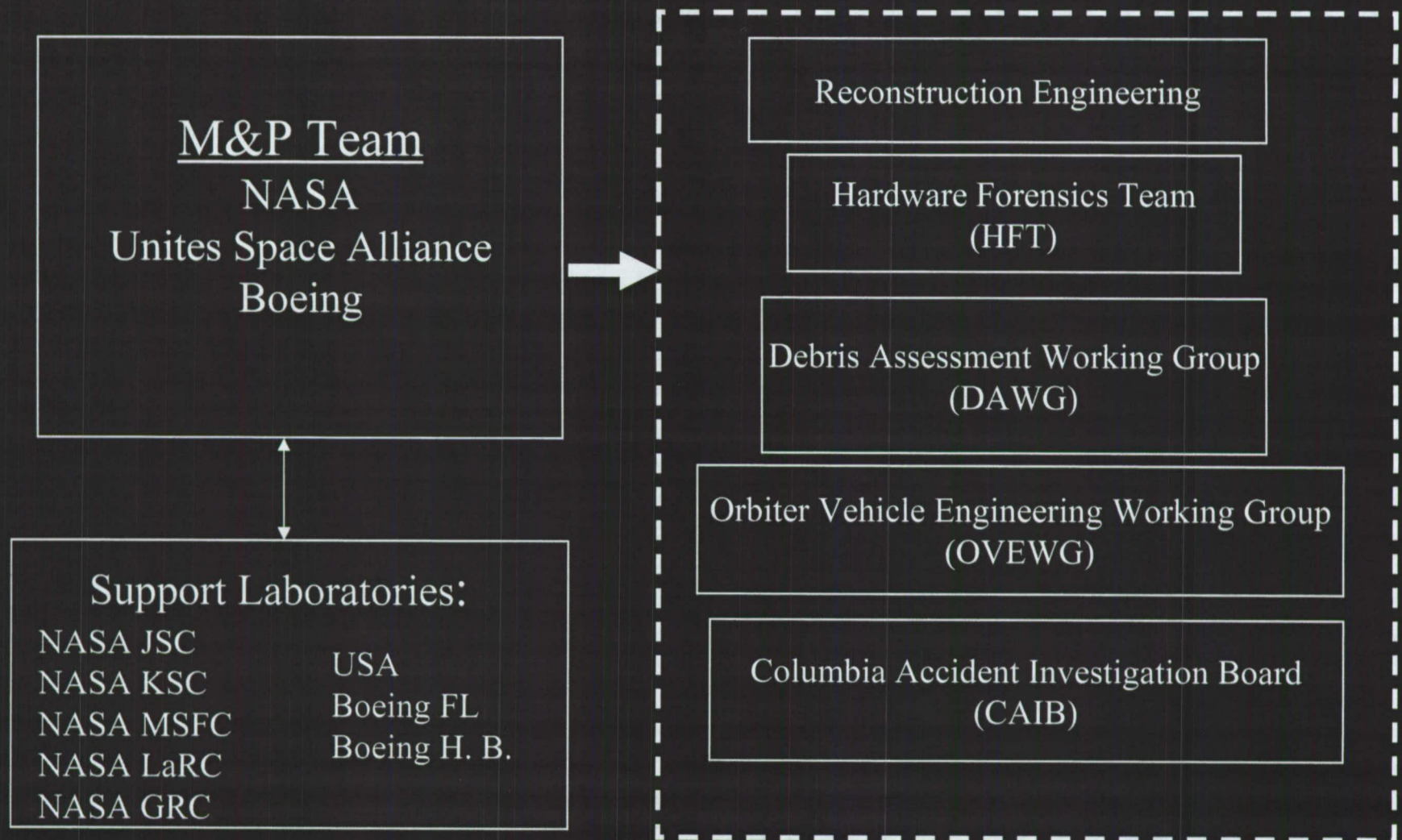
Nemotodes (round worms) Experiment



Columbia Recovery and Reconstruction Statistics

- Over 16,000 people at recovery sites
- 1.5 million hours expended in search and recovery effort
- 150,000 hours expended in reconstruction phase
- Approximately 84,000 pieces retrieved
- Approximately 85,000 lbs of debris retrieved, representing approximately 38% of the Orbiter's dry weight
- Debris Reconstruction Team at KSC – 150 people

M&P Engineering Team



The M&P Team gratefully acknowledges the talents and contributions of the following individuals:

NASA-GRC

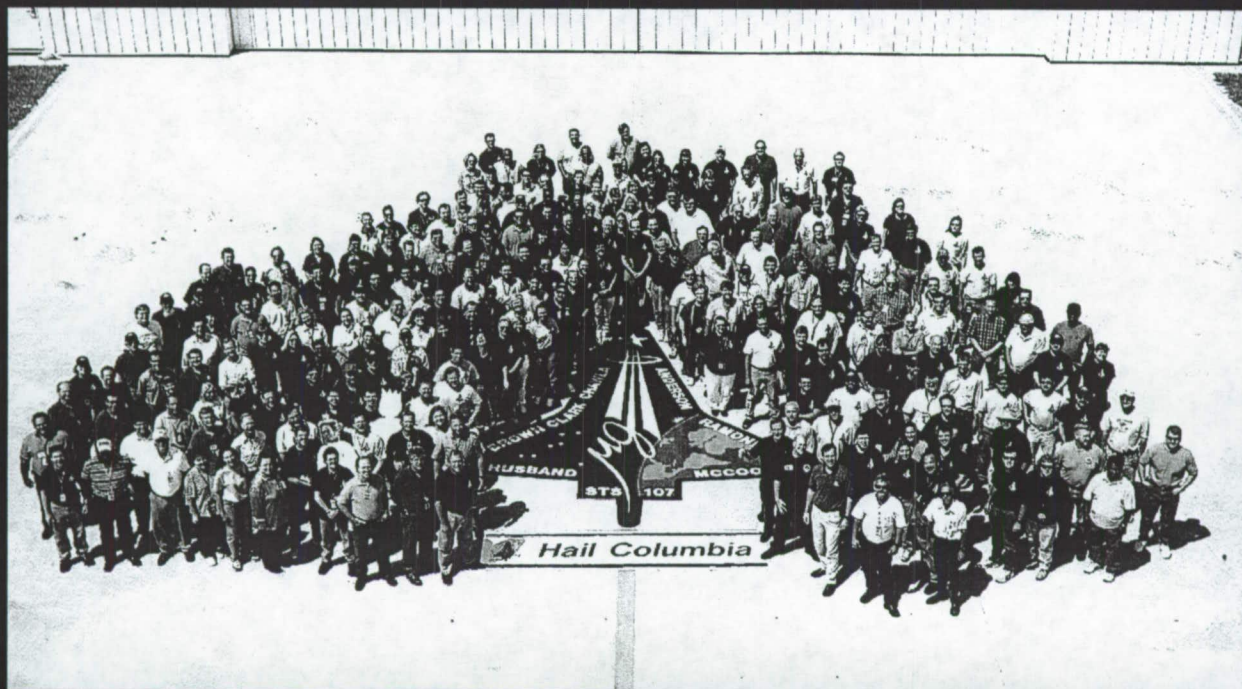
- Herb Garlick
- Leslie Greenbauer-Seng
- David Hull
- Nathan Jacobson
- Elizibeth Opila
- James Smialek

NASA-JSC

- Jay Bennett
- Glenn Ecord
- John Figert
- Julie Henkener
- Julie Kramer-White

NASA-KSC

- Larry Batterson
- Virginia Cummings
- Dionne Jackson
- Thad Johnson
- Hae Soo Kim
- Sandra Loucks
- Peter Marciniak
- Wayne Marshall
- Orlando Melendez
- Scott H. Murray
- Jaime Palou
- Donald Parker
- Victoria Salazar
- Eric Thaxton
- Stan Young



NASA-LaRC

- Robert BERRY
- Stephen Smith
- William Winfree

NASA-MSFC

- James Coston
- Greg Steele

Boeing

- Rodger Capps
- Tab Crooks
- Jeff Hausken
- Stephanie Hopper
- Mark Hudson
- Dave Lubas
- Robert Perez
- Keith Pope
- Janet Ruberto
- Keith Pope
- Jim Stewart

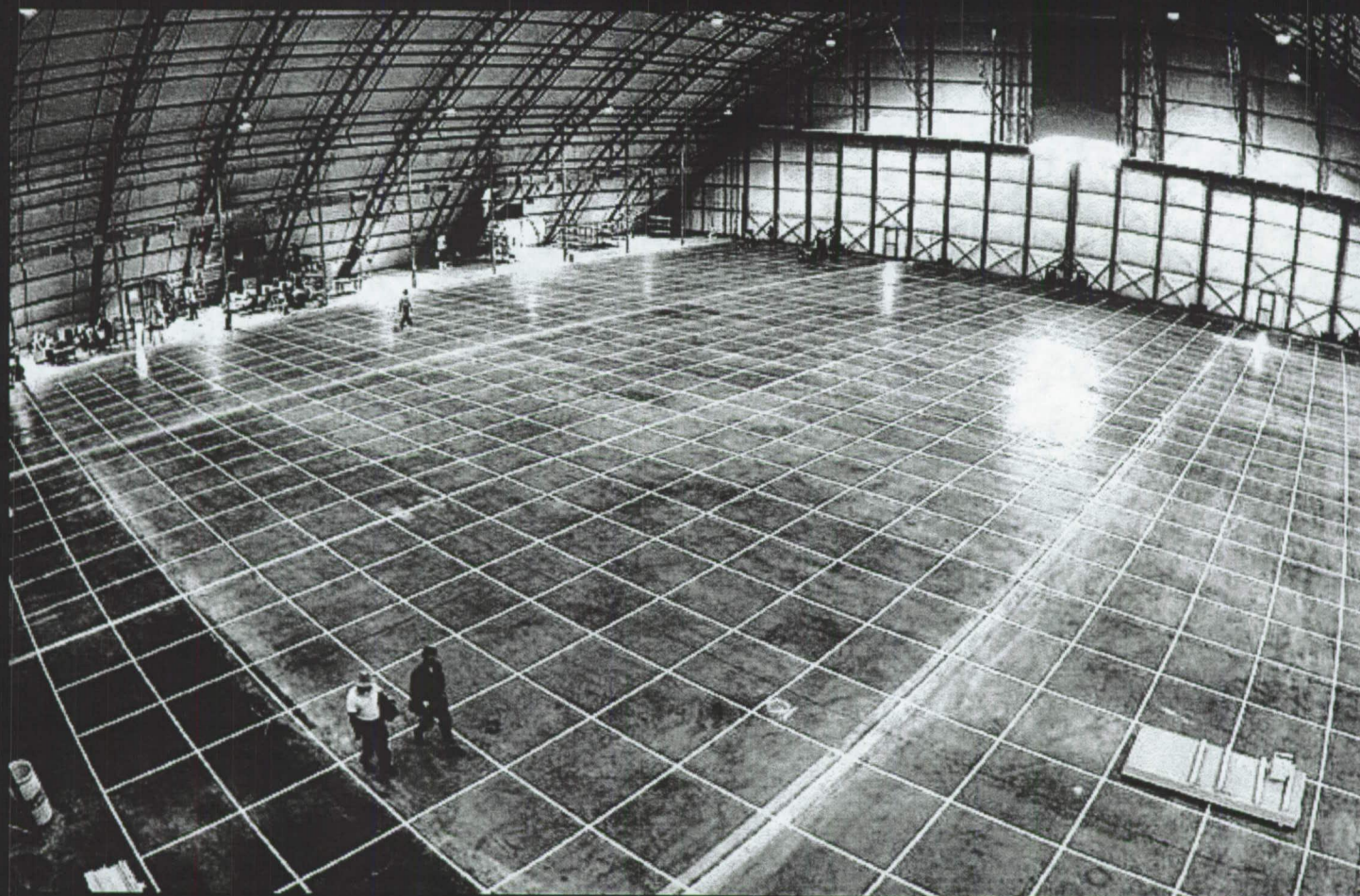
USA

- Cathy Clayton
- Stanley Schultz
- Bryan Tucker

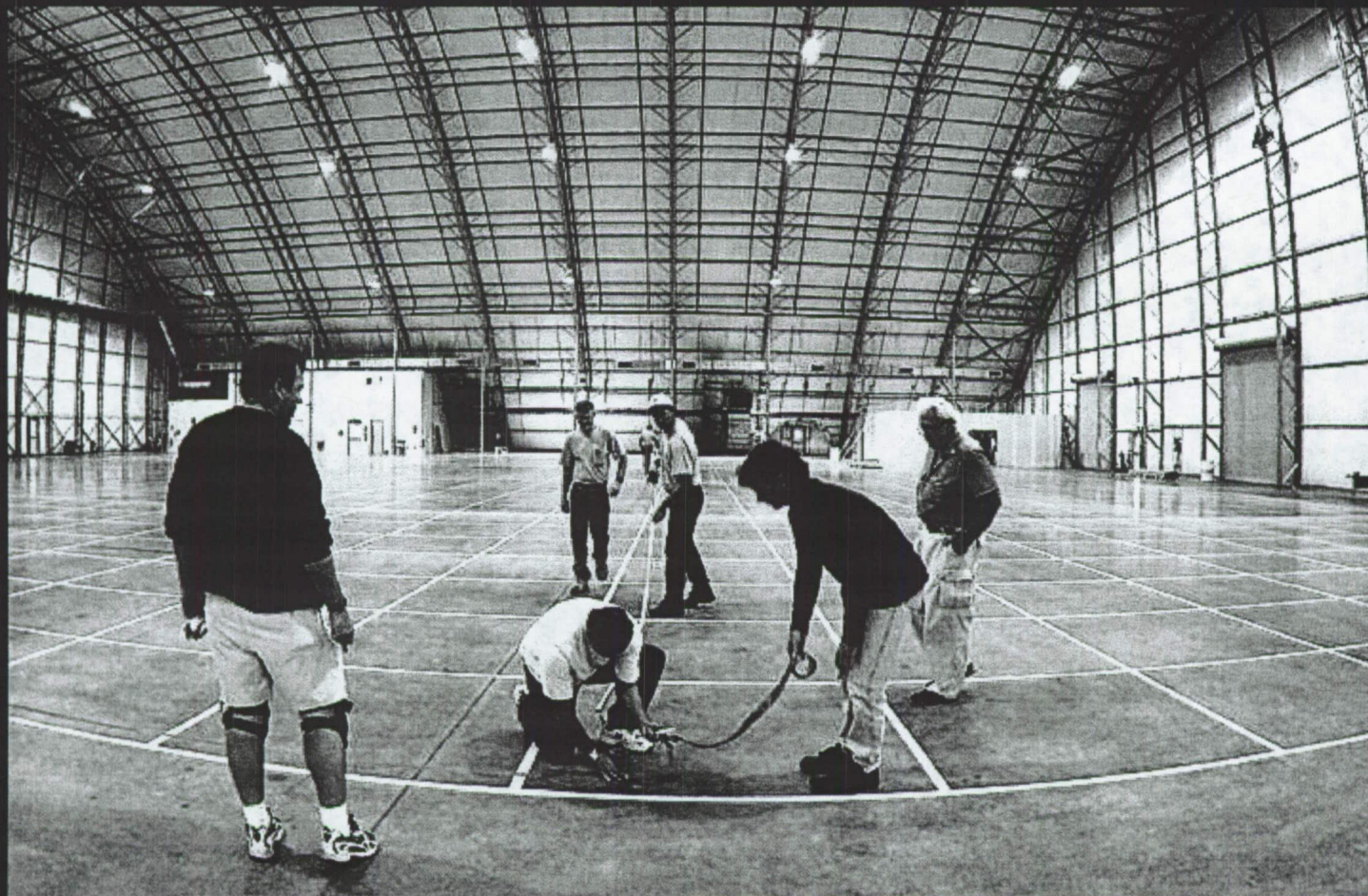
CAIB

- Dr. Gregory T. A. Kovacs
- G. Mark tanner

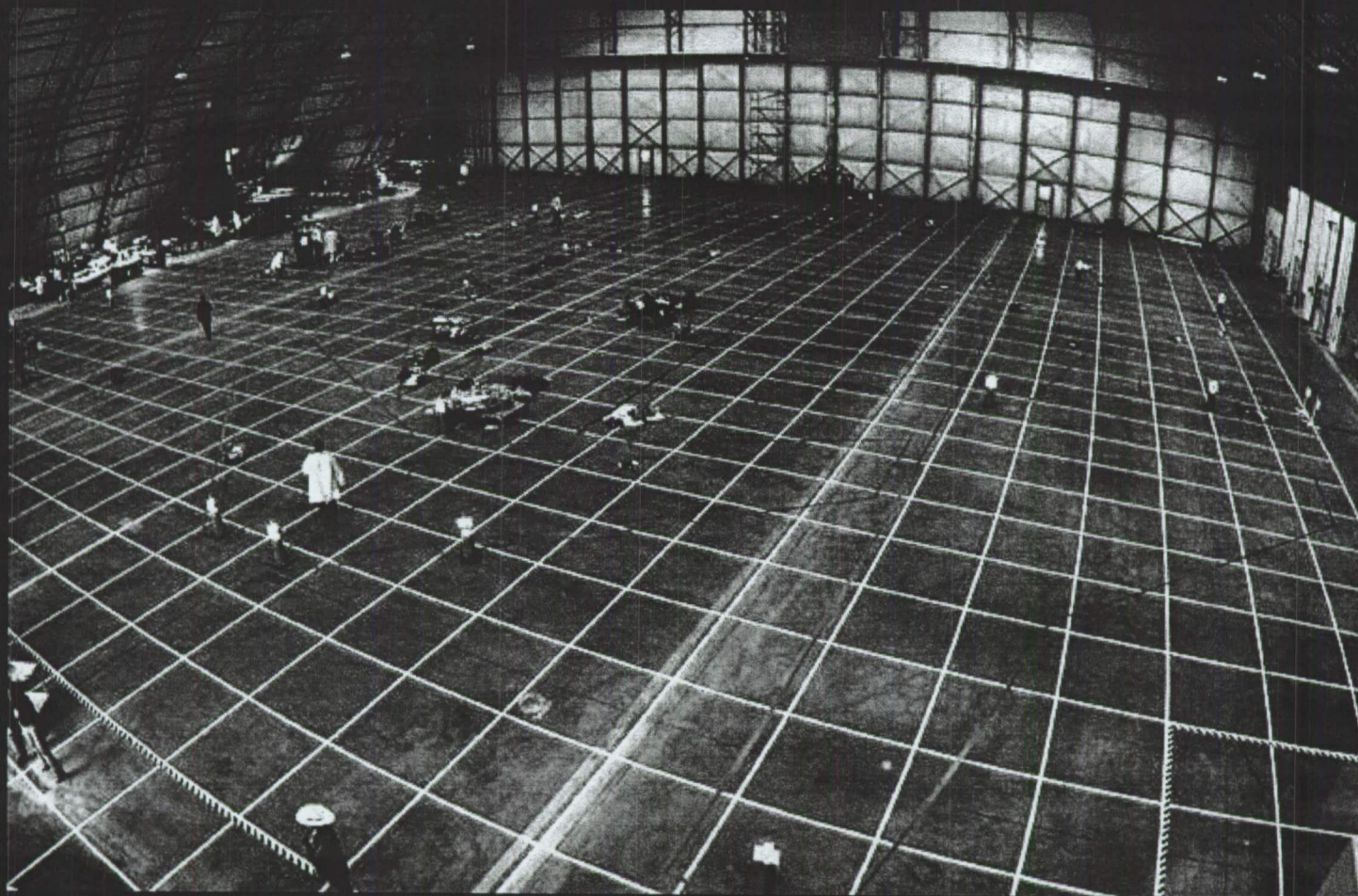
Reconstruction Hangar: 2-04-03



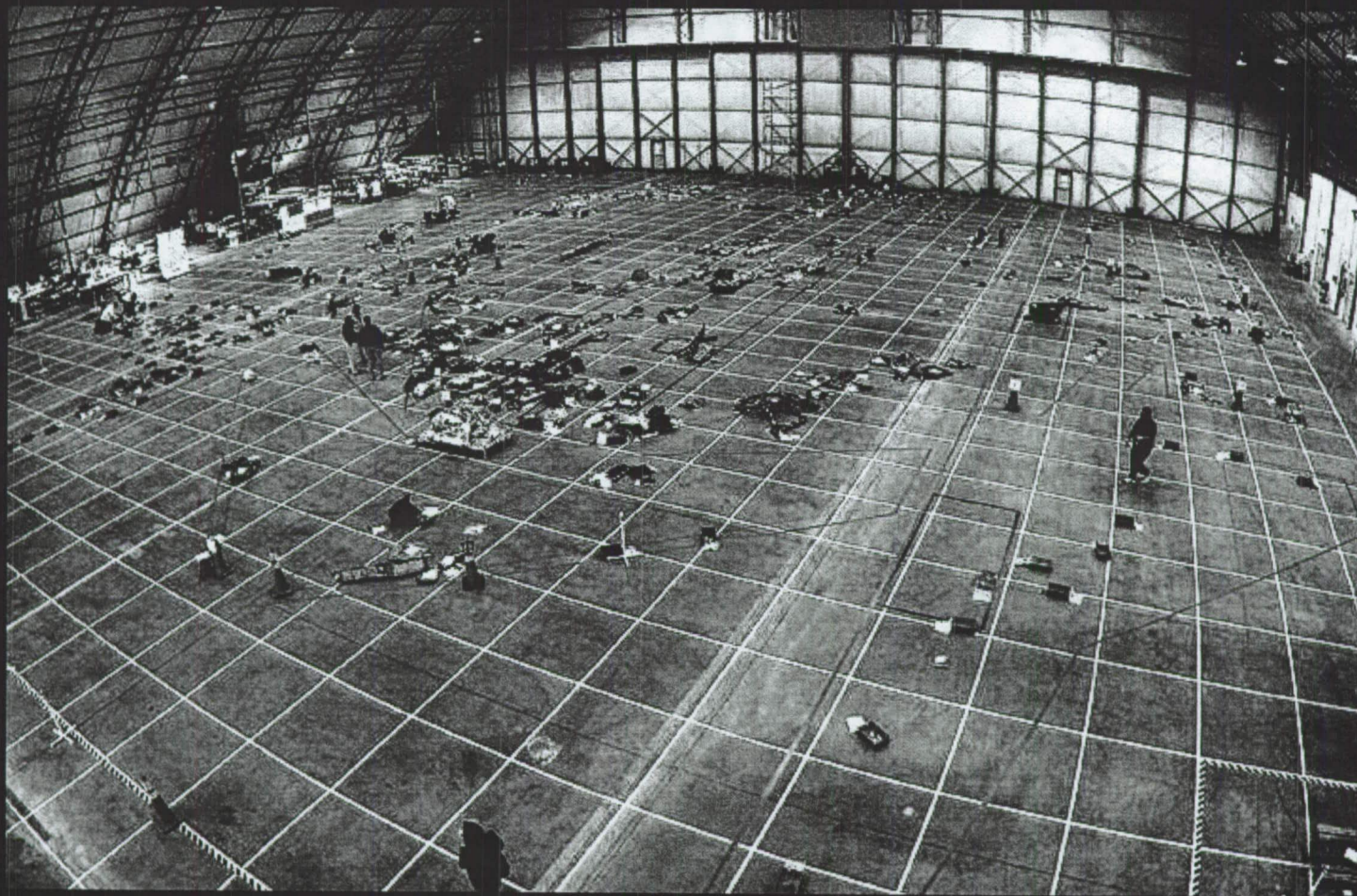
Reconstruction Hangar: 2-07-03



Reconstruction Hangar: 2-14-03



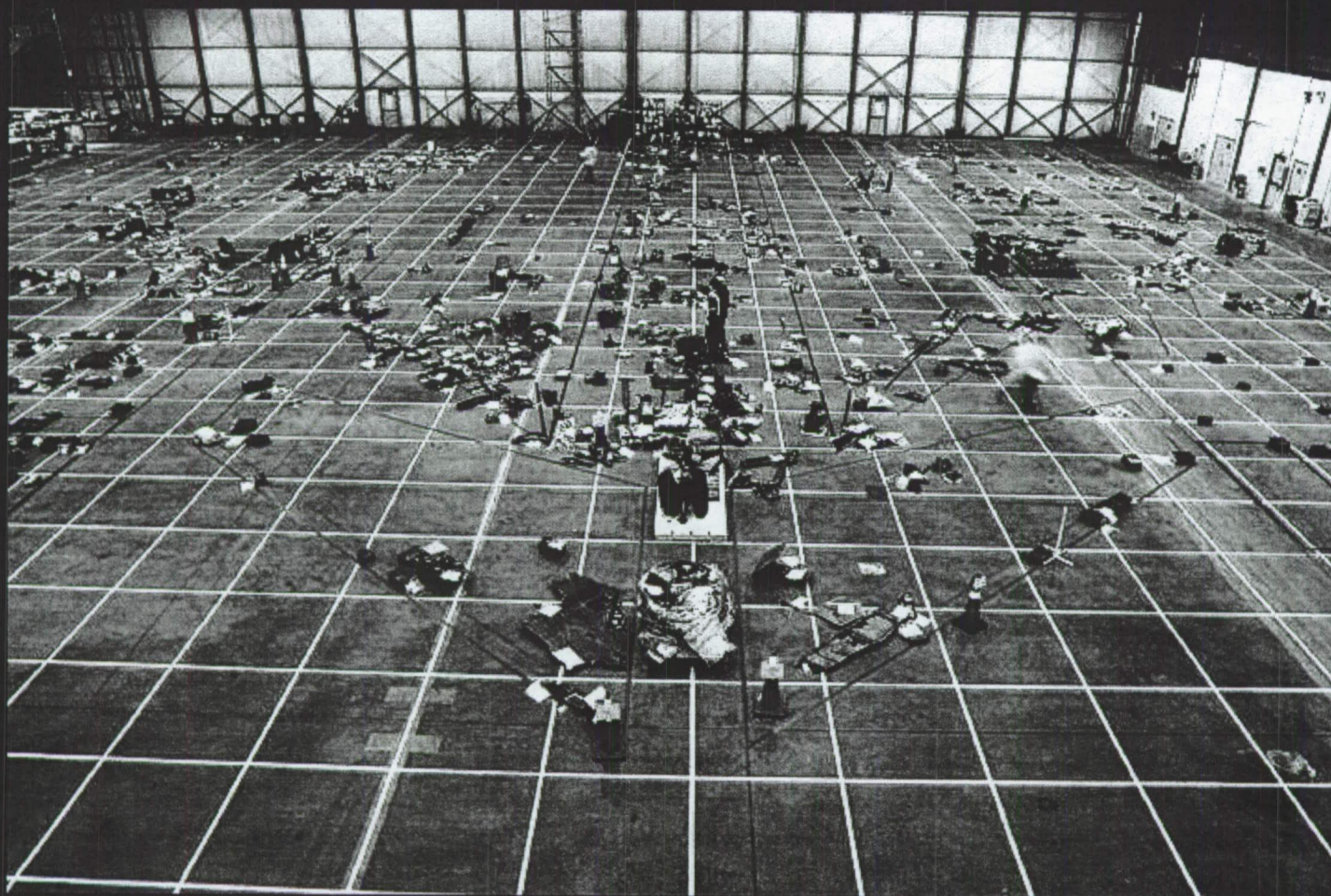
Reconstruction Hangar: 2-20-03



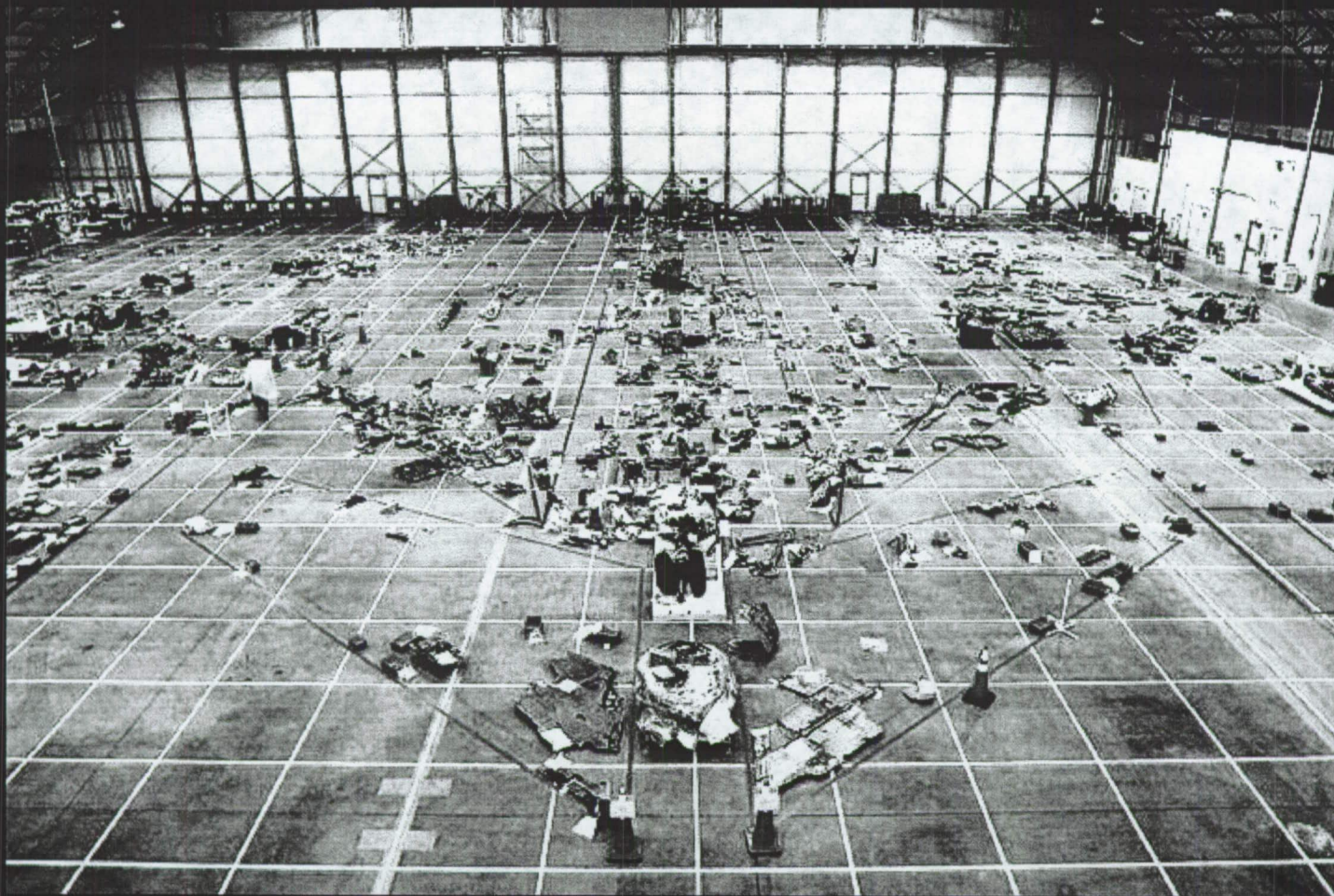
Reconstruction Hangar: 03-04-03



Reconstruction Hangar: 03-12-03



Reconstruction Hangar: 03-20-03



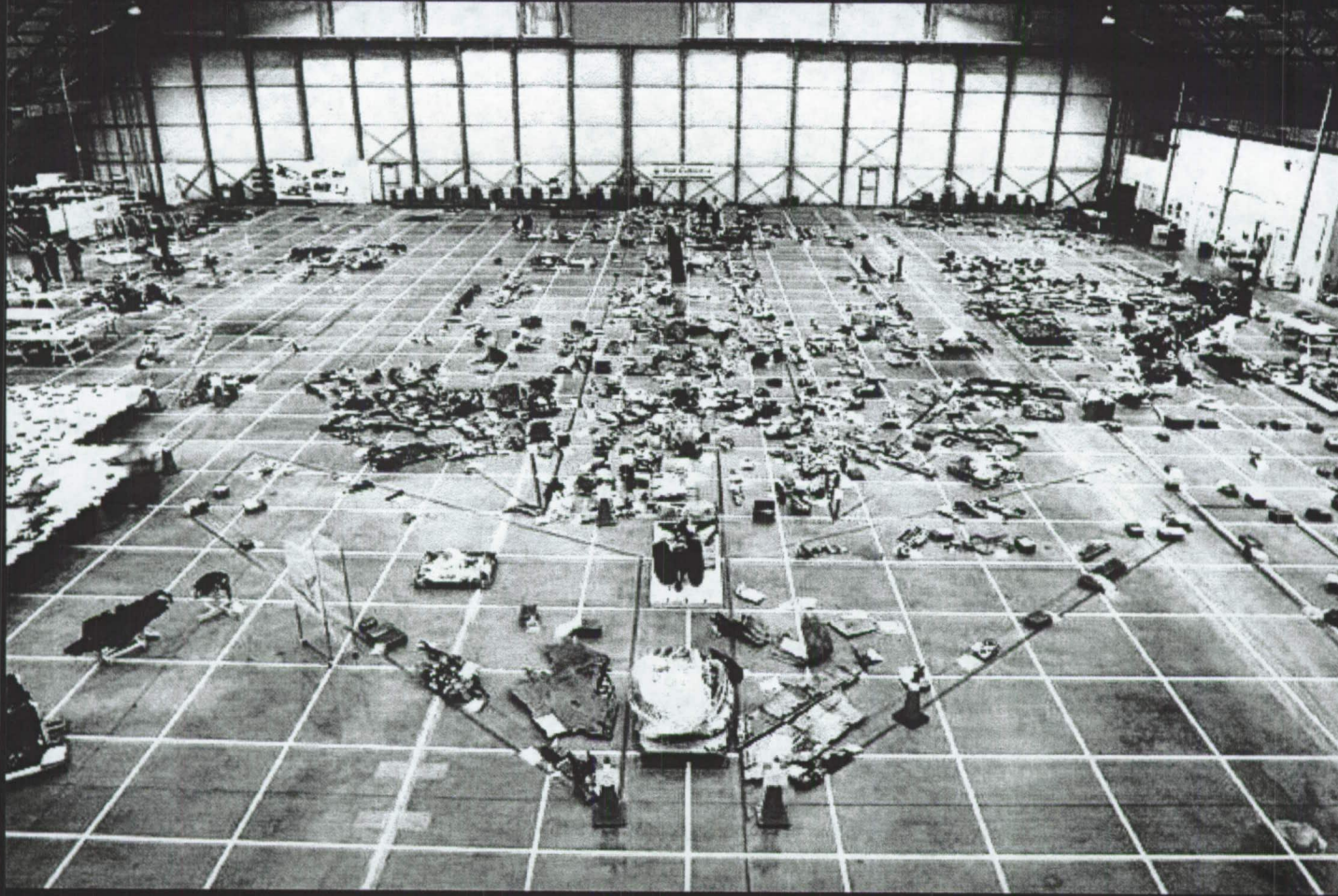
Reconstruction Hangar: 03-26-03



Reconstruction Hangar: 04-17-03



Reconstruction Hangar: 05-22-03



Reconstruction



Reconstruction: From Left Wing



Reconstruction: Right Wing



Reconstruction: Tiles



Reconstruction: Tiles

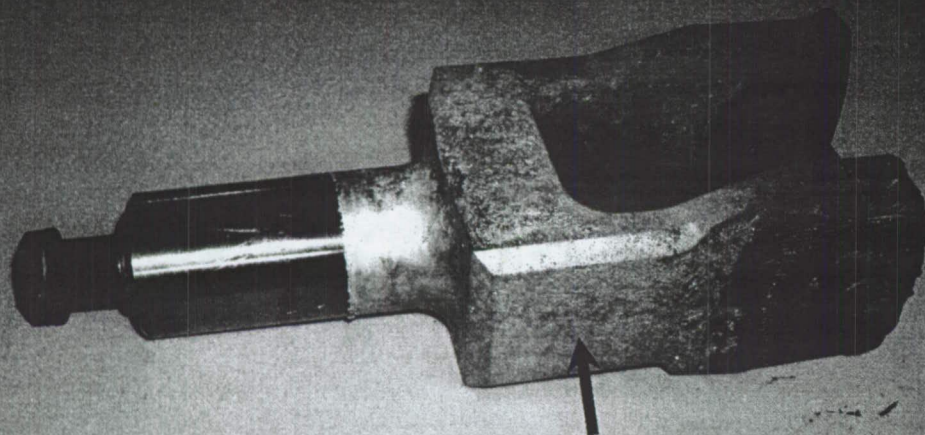


Left Outboard Main Tire

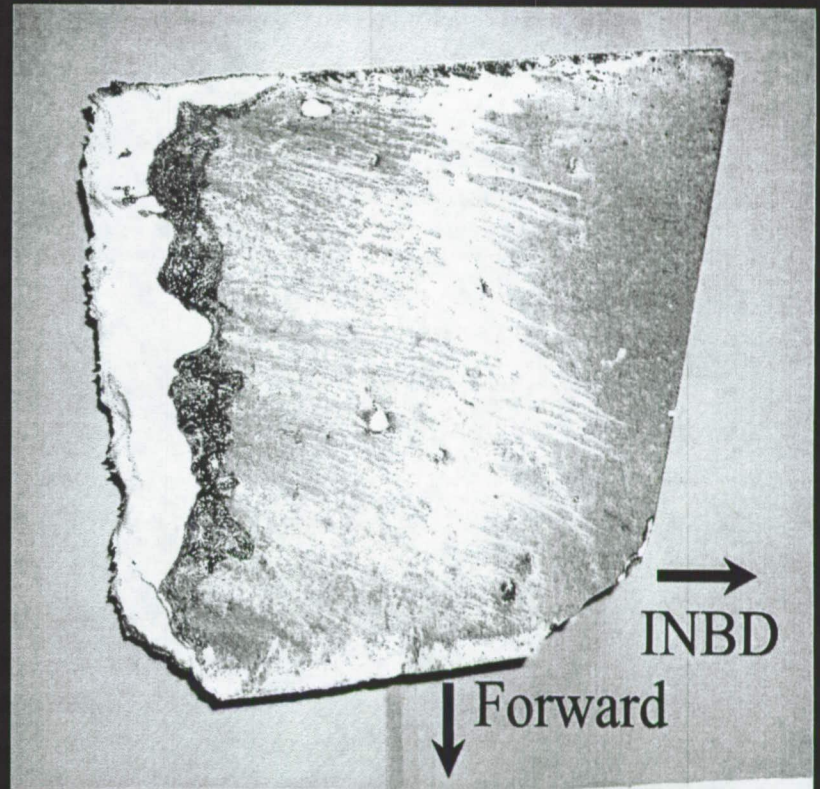


Debris

Main Landing Gear Uplock Roller



Heaviest splatter on
inboard side



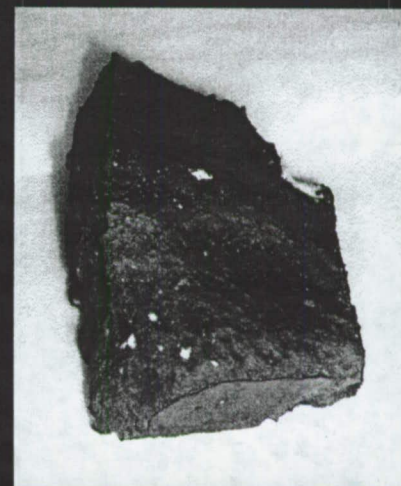
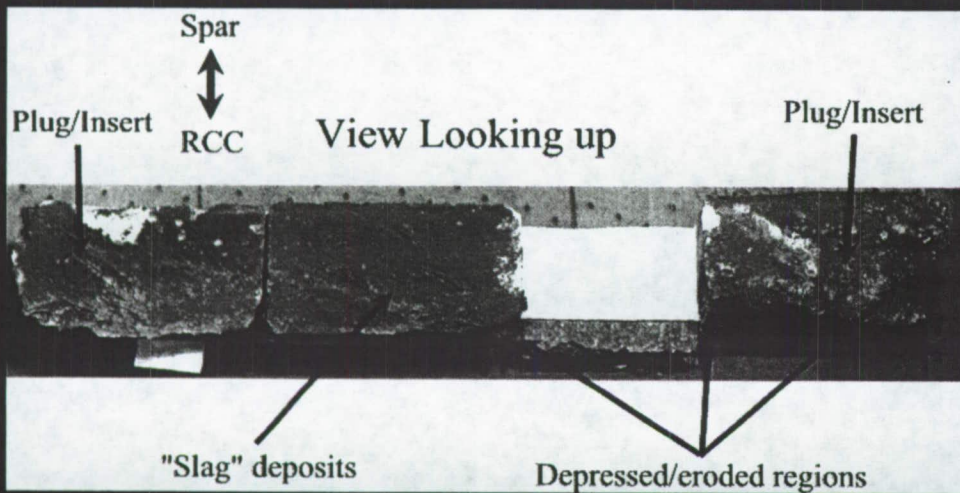
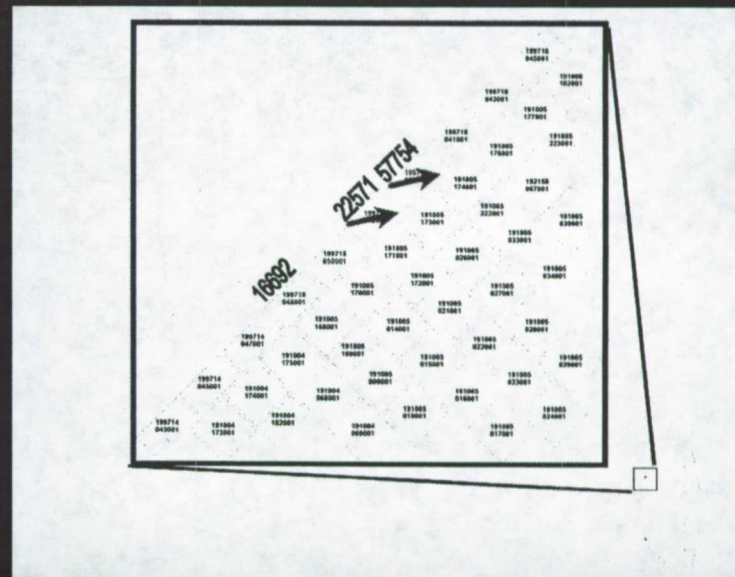
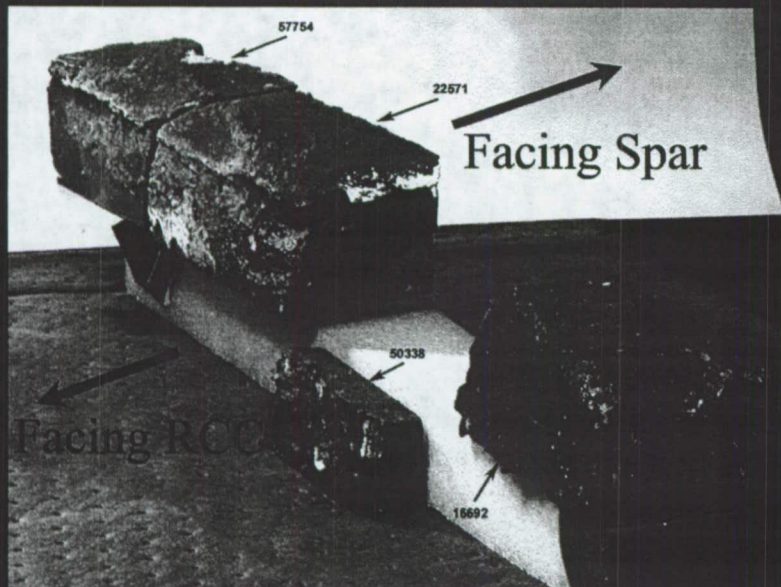
Main Landing Gear – Corner Tile

Debris

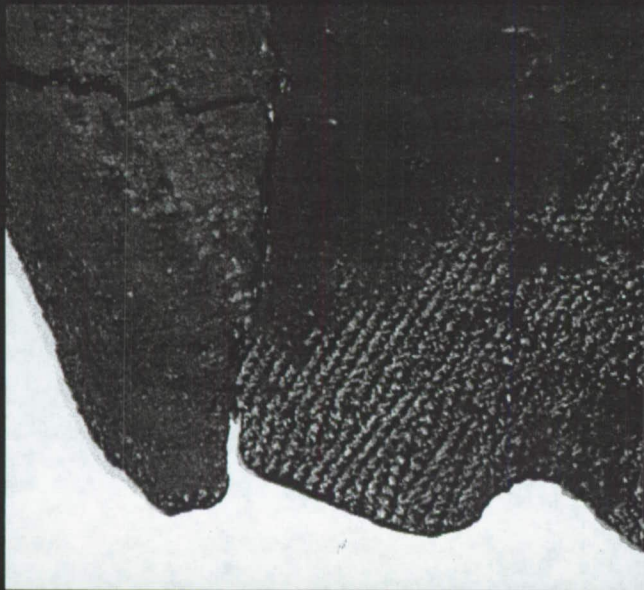


Midbody Panel- Erosion and tile
damage

Carrier Panel Tiles

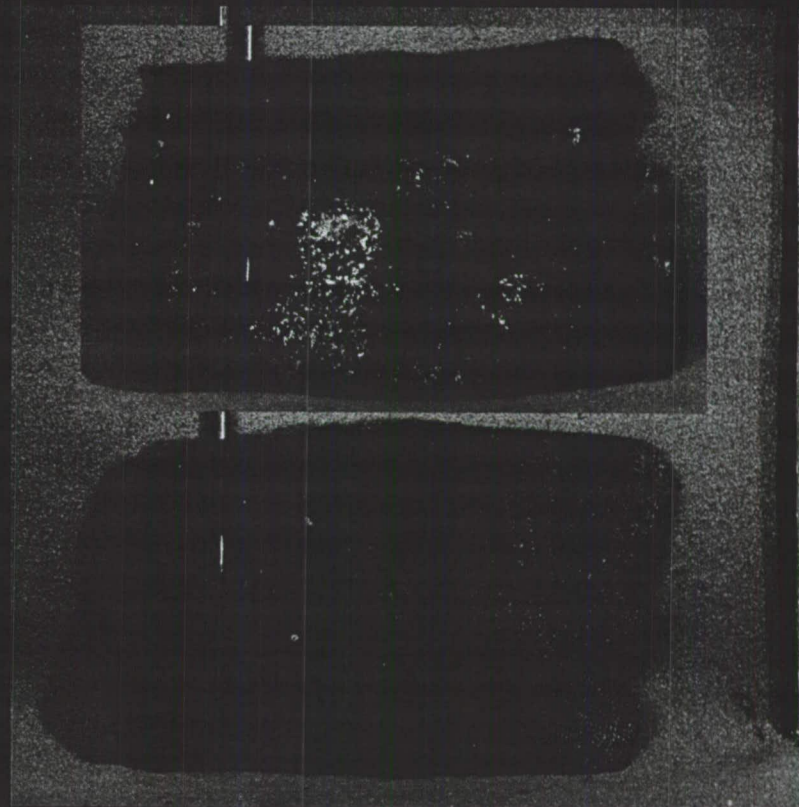


RCC

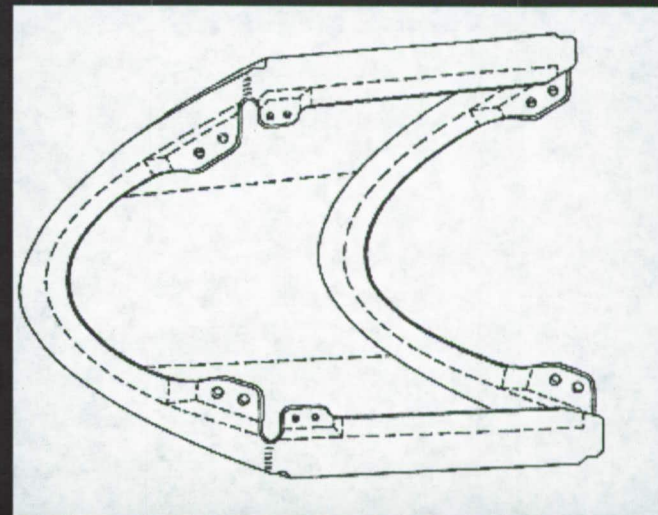
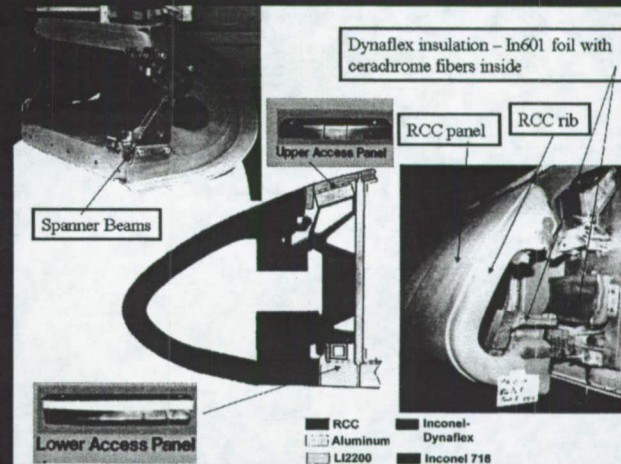
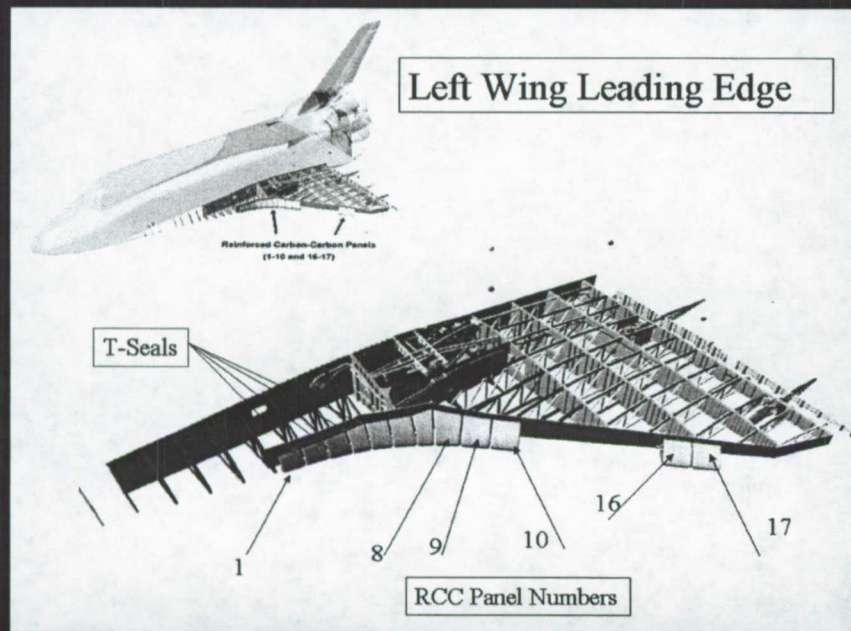


Mating LH RCC #8 Fragments

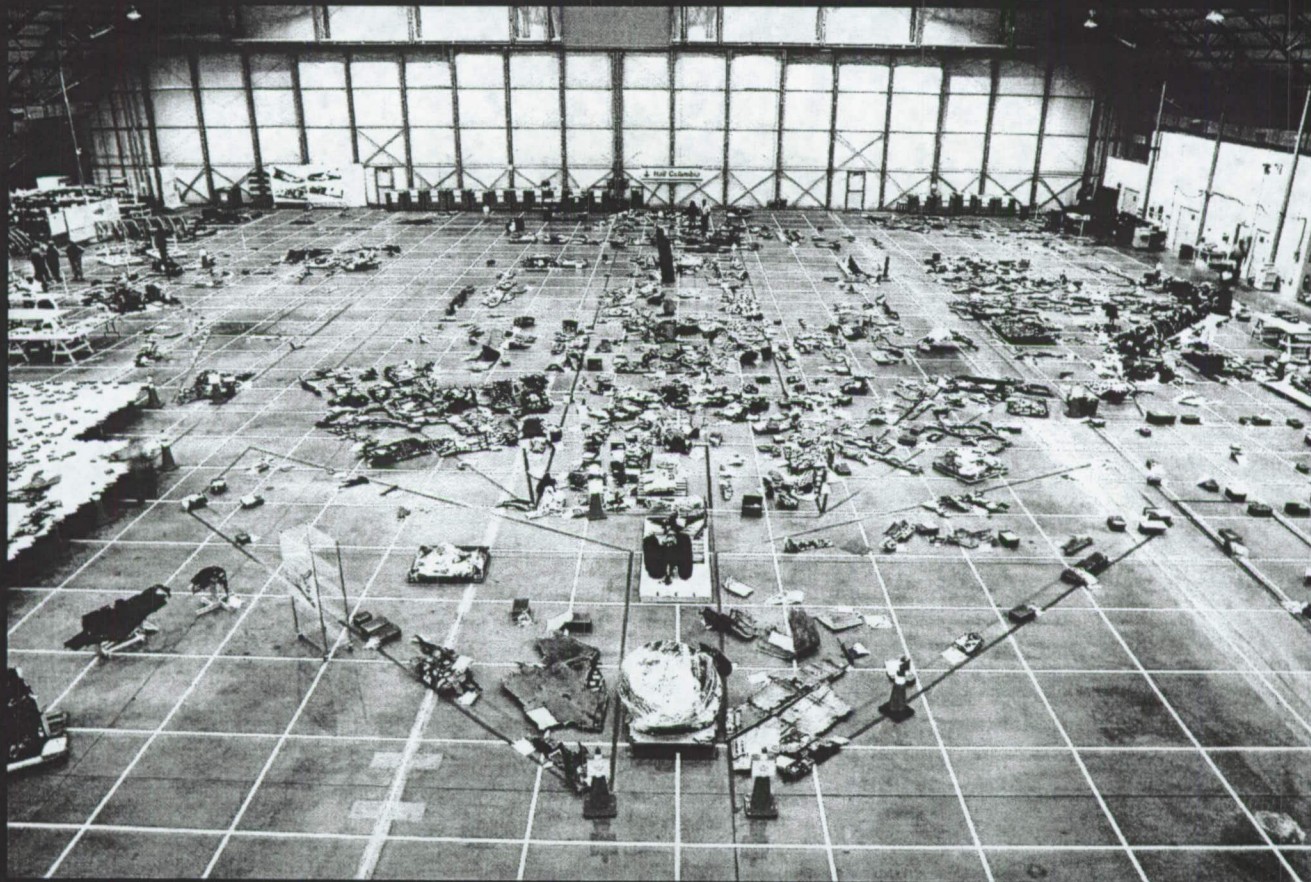
LH RCC #8 fragment (2 views)



Leading Edge Representation



STS-107 Reconstruction Hangar



Initially, analysis was restricted to visual and macroscopic examination of debris in the hangar.

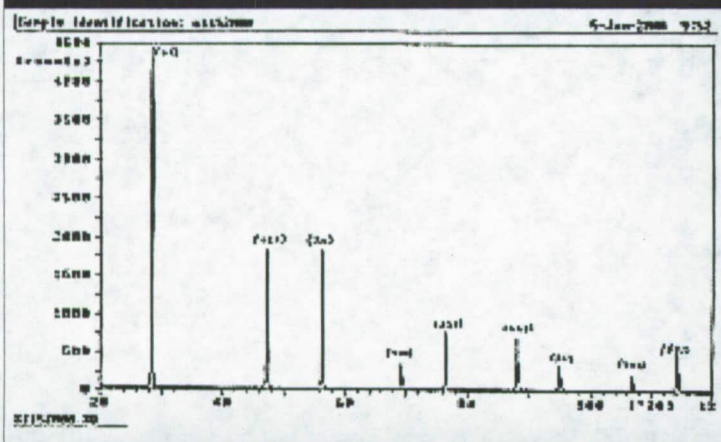


Analytical Techniques

Technique	Purpose	Benefit
Photography	Photo documentation	Documentation to maintain traceability
Scanning Electron Microscopy – SEM/EDS	Semi-quantitative elemental composition	Elements present, identify difference between top and bottom of sample
X-ray Diffraction – XRD	Identify compounds	Identify compounds of crystalline structure
Electron Microprobe	Identify elements	Determine exact composition
Fourier Transform Infra-Red – FTIR	Qualitative organic composition	If organic, aid in identification
ESCA/XPS	Identify inorganic & organic compounds	Aid in tracking of oxidation states, such as oxide; compound identification
Metallography & SEM	Layering of material	Composition through deposit layers
Inductively coupled plasma - ICAP	Quantitative elemental composition	Elements present, Quantify bulk composition of sample
NDE Inspections- Radiography, CT, Ultrasonics	Non-destructive Inspection and identification	See through the material, identify differences in materials, identify defects

Typical EDS, XPS, and XRD results:

XRD



A1 inner

Region 1

Region 2

Region 3

Region 4

Region 5

Region 6

Region 7

ESCA/XPS

Pressure: 1×10^{-8} torr

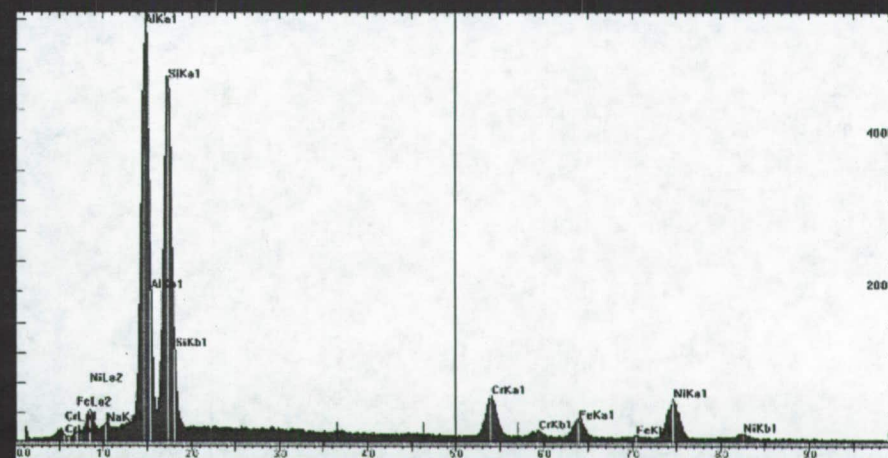
Conditions: Magnesium X-rays at 15 KV and 12 mA

Element	Position, Binding Energy (eV)	Possible Compound(s)	Mass Concentration (weight %)
O 1s	532.050		58.29
Al 2p	75.050	Al ₂ O ₃ , minor Aluminum silicate	22.29
Fe 2p	710.050	FeO and Fe ₂ O ₃	2.47
Cr 2p	575.750	CrO ₂	7.61
Cu 2p	932.850	Cu metal	2.20
Si 2p	102.550	Al silicate	5.23
N 1s	399.150		1.91

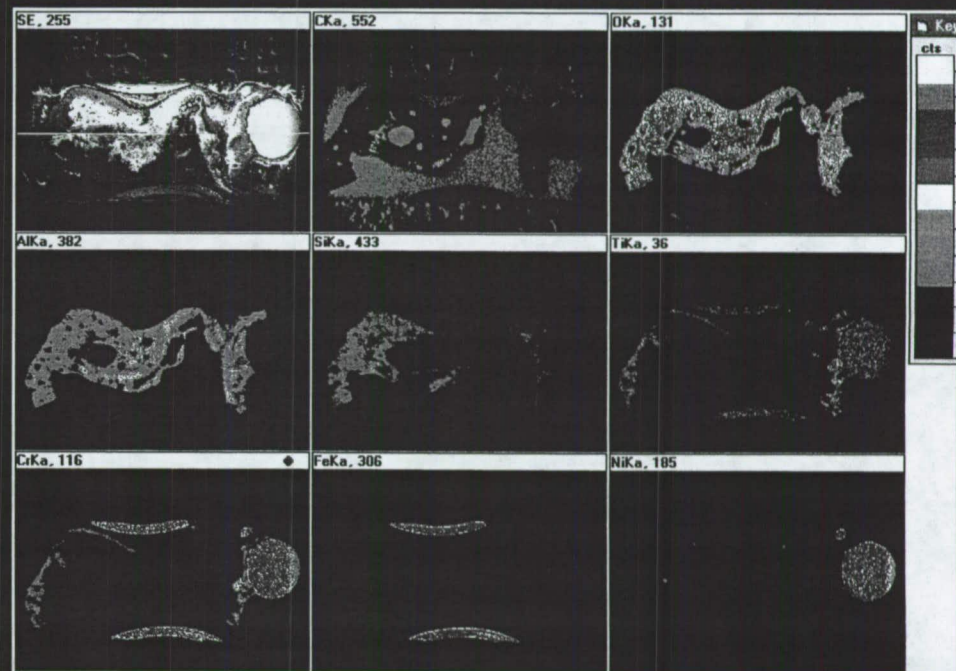
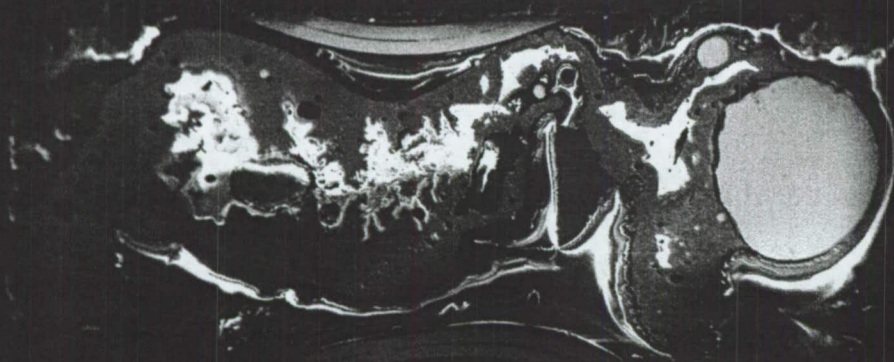
EDS

Elements Detected (Approximate Weight %) via SEM/EDS

Na	Mg	Al	Si	Ca	Ti	Cr	Fe	Ni	Cu
<1	-	33	38	-	-	8	5	15	-
<1	-	32	37	-	-	8	5	18	-
<1	-	32	37	-	-	7	5	19	-
-	-	31	31	-	-	7	7	24	-
-	-	29	29	-	-	8	7	26	-
-	-	30	30	-	-	8	7	26	-
-	-	31	34	-	-	7	6	22	-



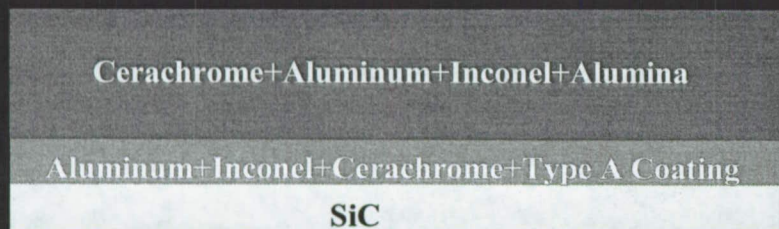
SEM/EDS



NASA KSC LABS DIVISION
 KSC-MSL-2003-0143-01
 RDS 18477-1 Slag Sample E2 Dot Map

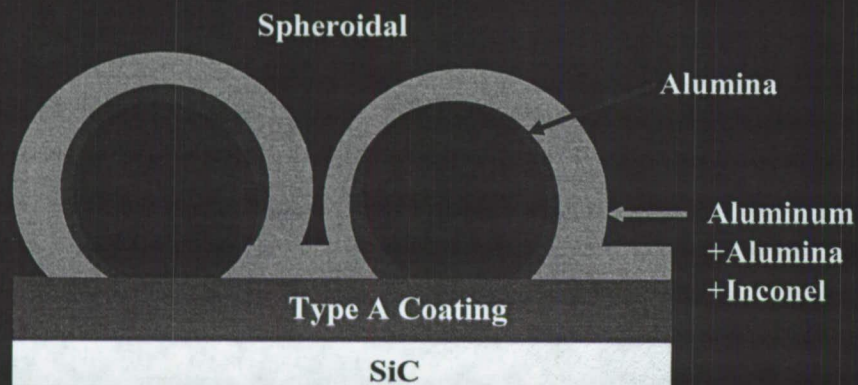
Mag = 16 X 200µm
 EHT = 25.00 kV
 WD = 19 mm
 Date :14 Apr 2003
 Time :18:16:47

Deposit types via Micro-Probe



Carbon-Carbon

Typical



Spheroidal

Type A Coating

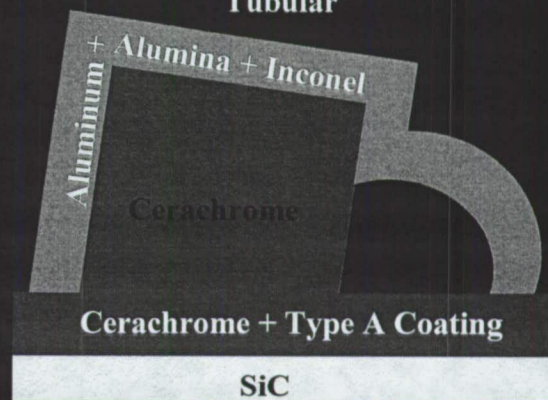
SiC

Carbon-Carbon



Carbon-Carbon

Globular



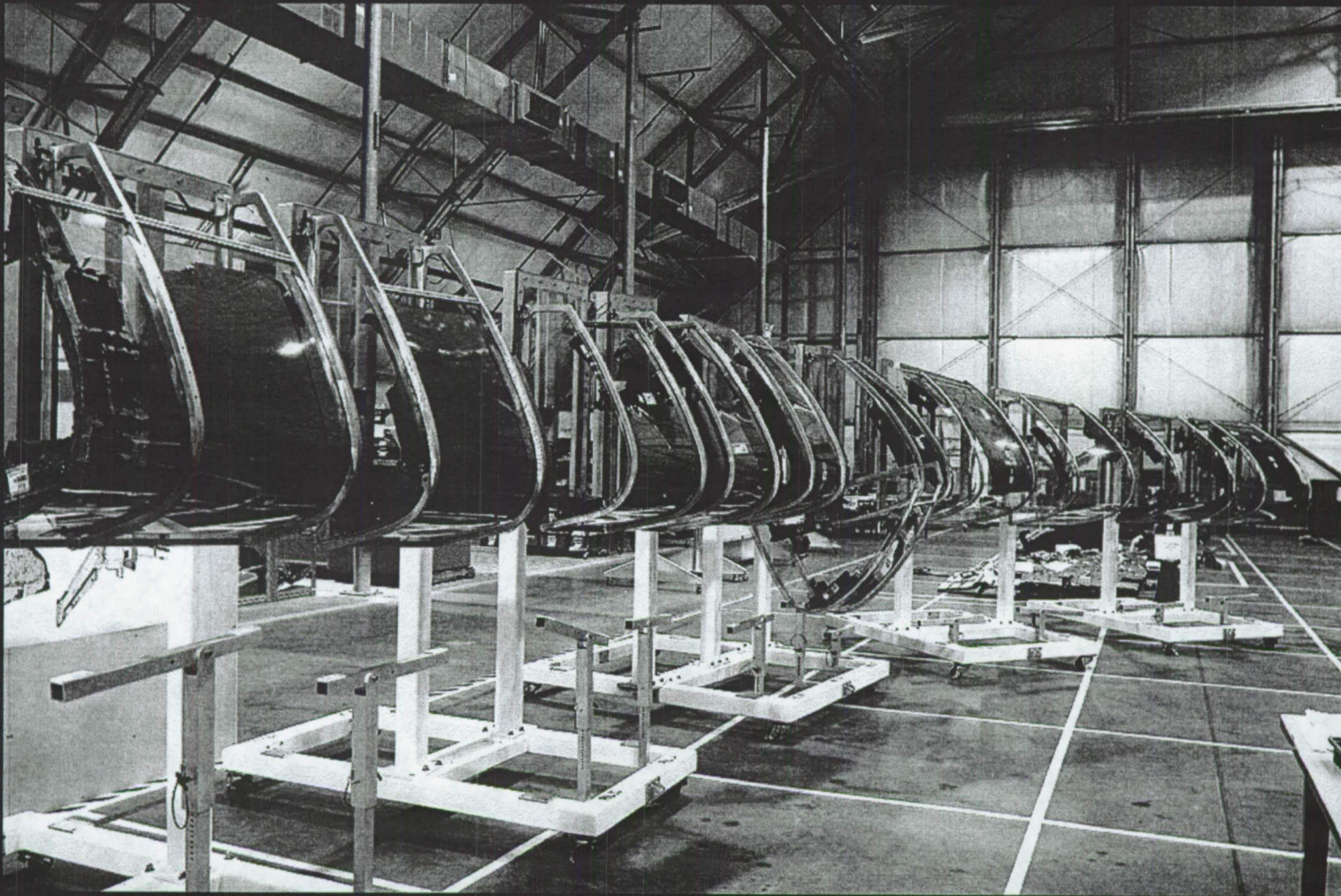
Tubular

Cerachrome + Type A Coating

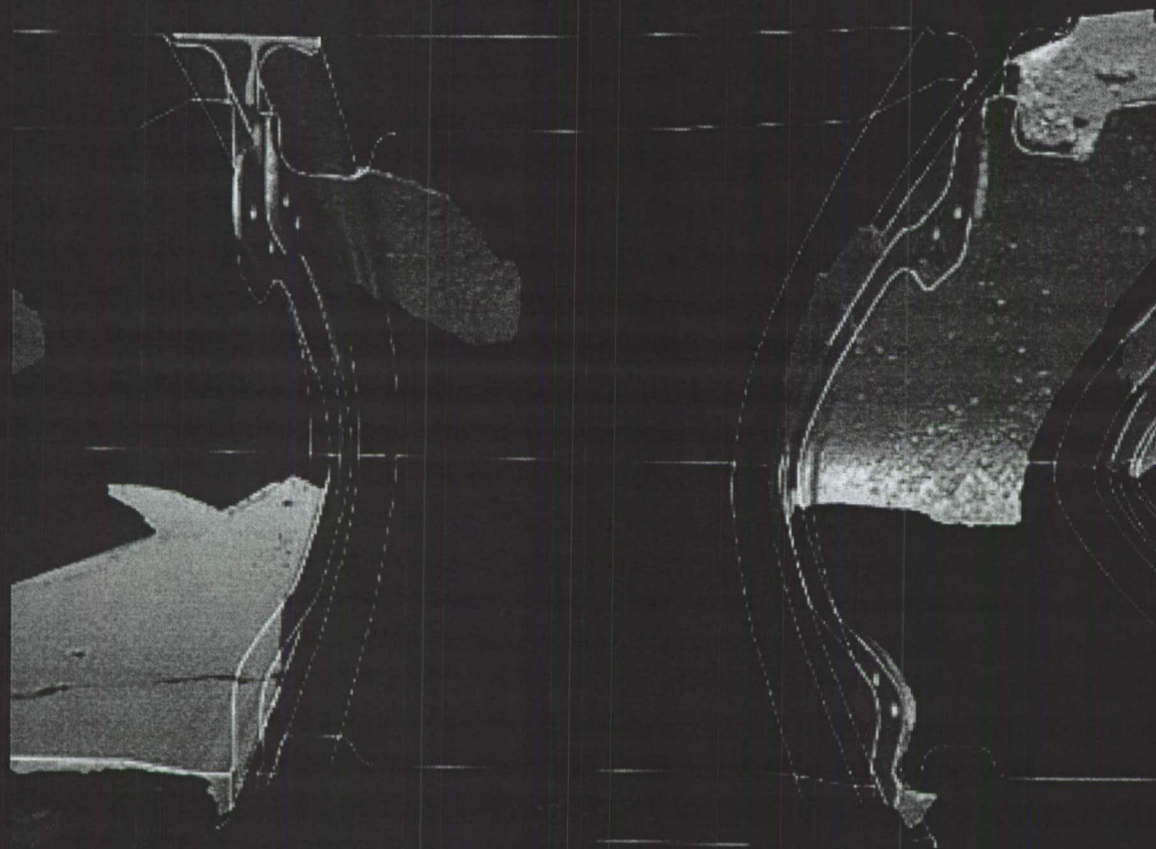
SiC

Carbon-Carbon

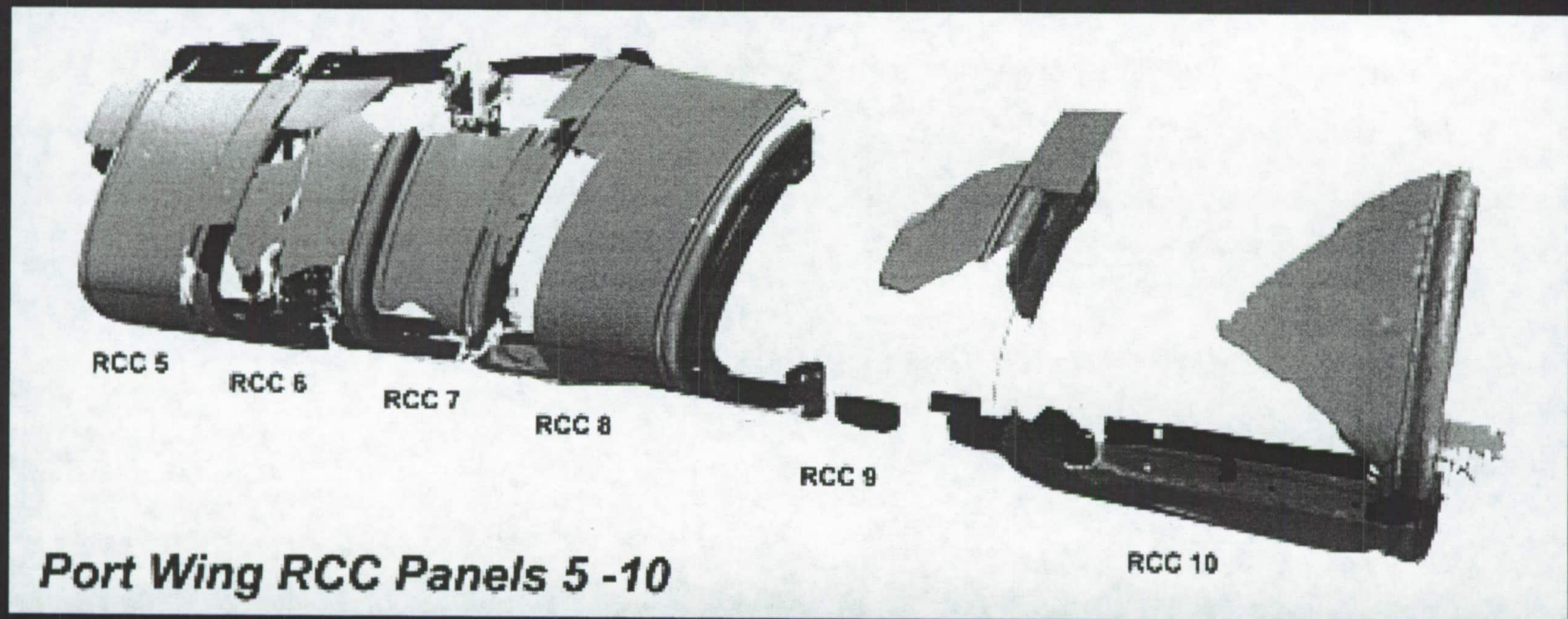
3D Reconstruction of Left WLE



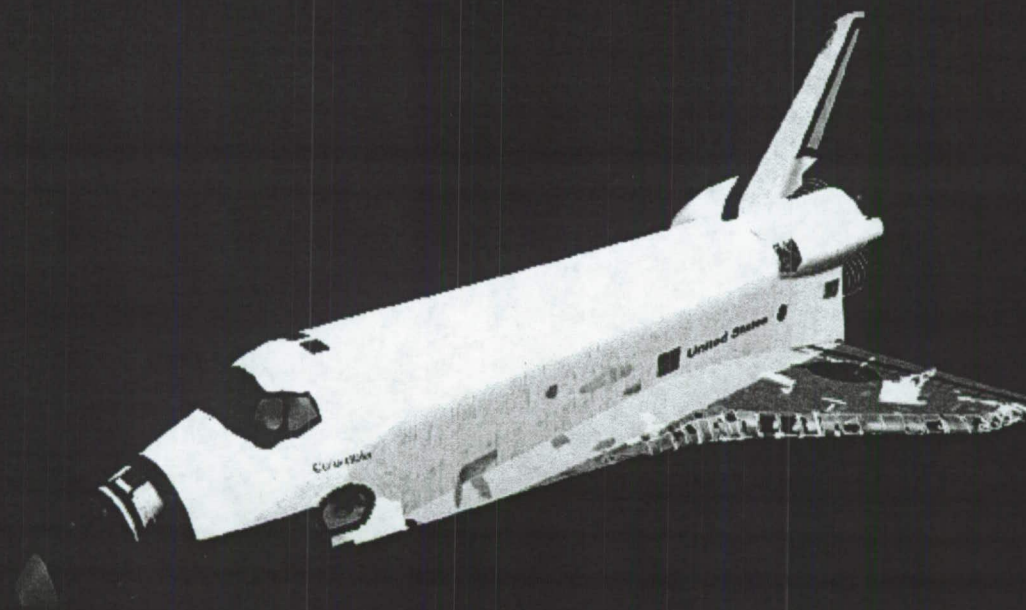
3D Reconstruction: Panels 8, 9, 10



3D Reconstruction



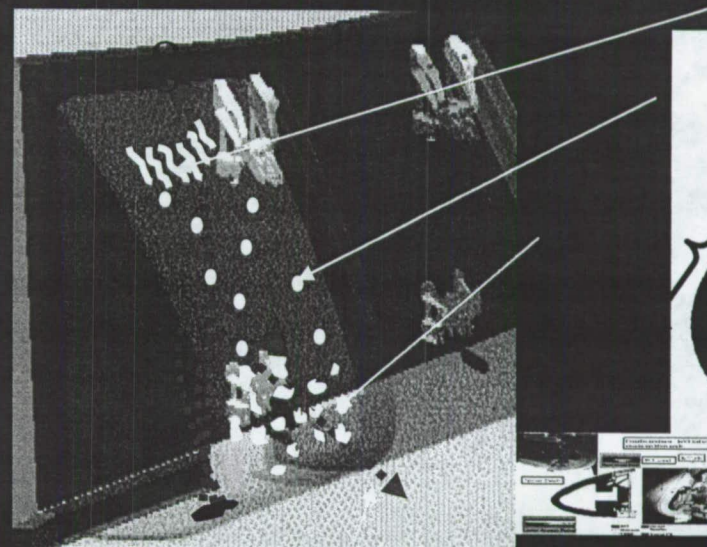
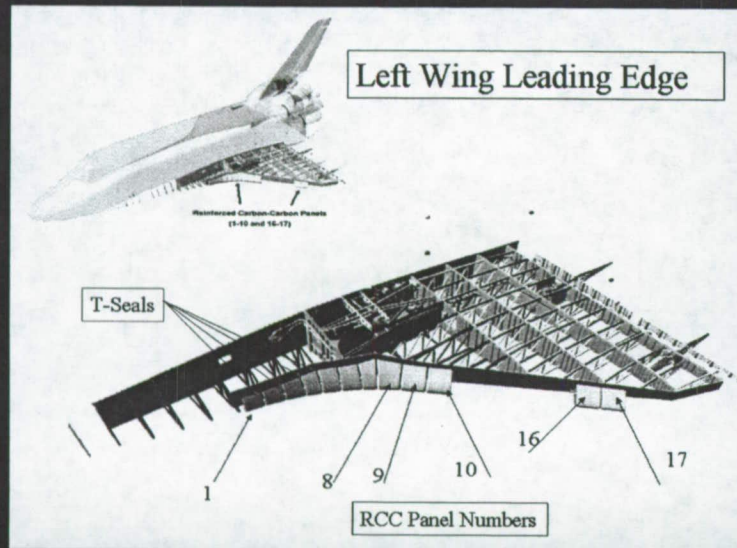
3D Reconstruction



3D Reconstruction Left Wing

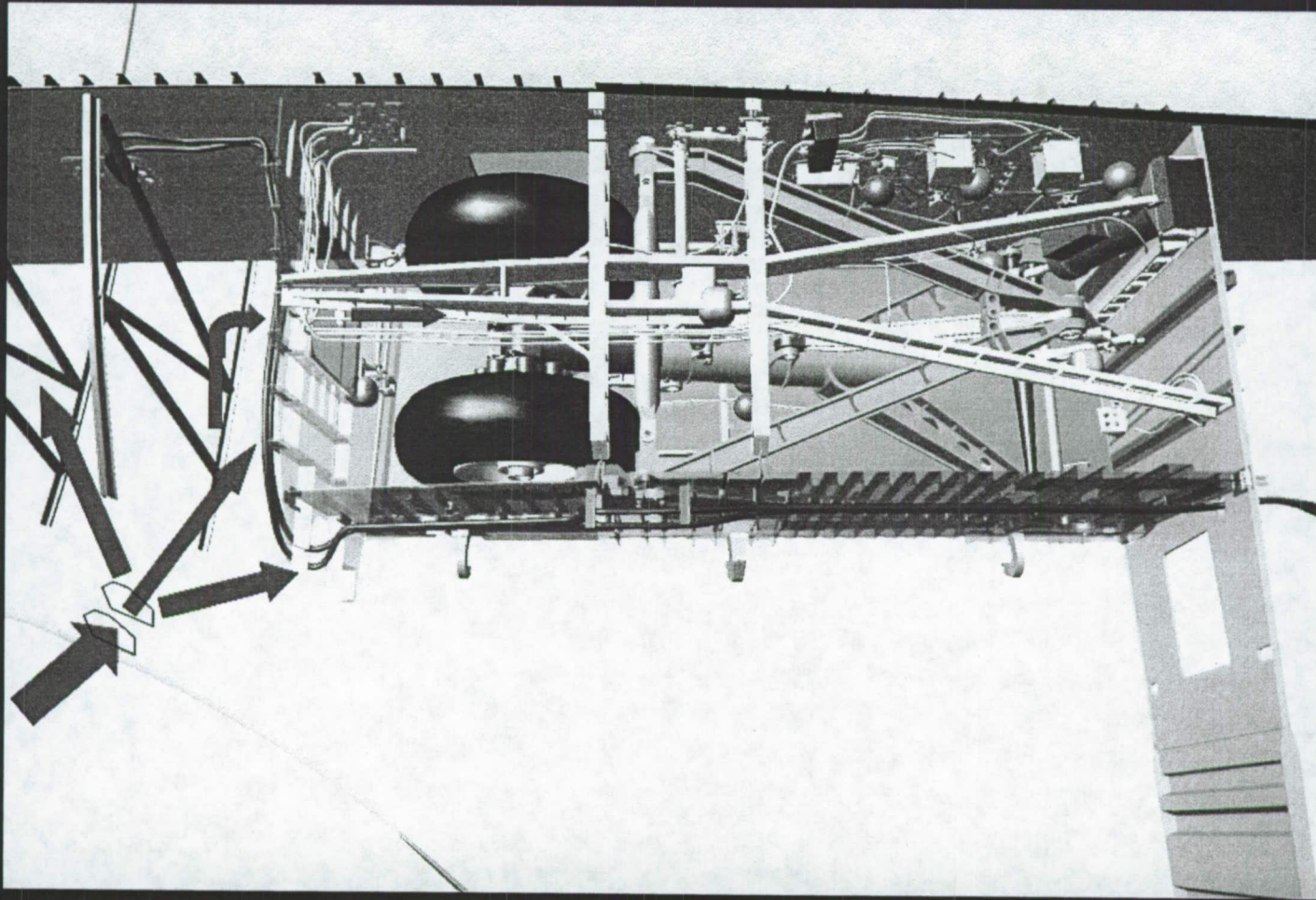


Failure Sequence

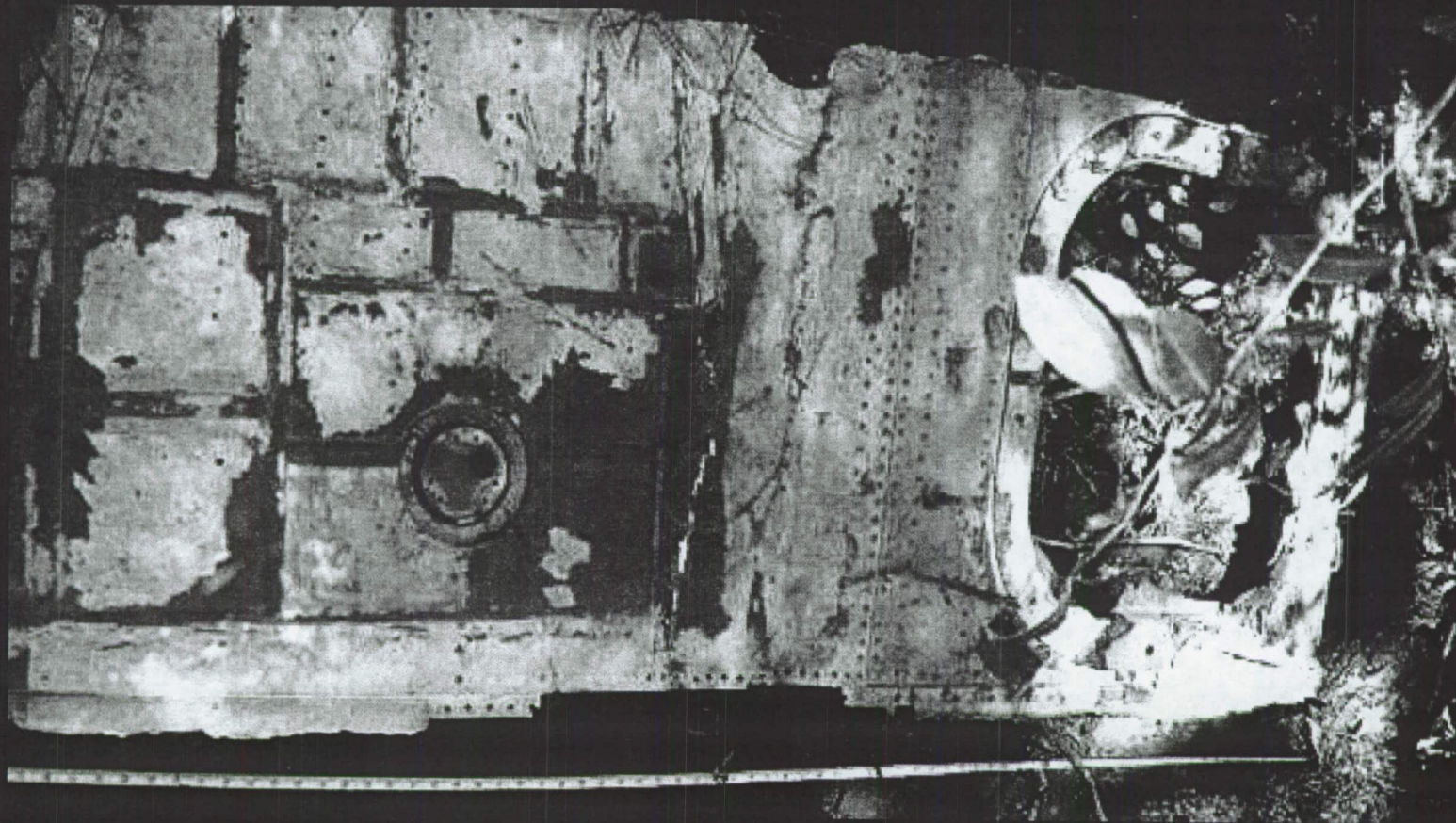


- Melting and vaporization of the Inconel 601 foil-covered cerachrome insulation blankets
- Slumping of the wing carrier panel tile immediately aft of the breach
- Erosion of the RCC adjacent to, and downstream of, the breach
- Melting and/or weakening of the Inconel 718 and A286 leading edge attach hardware
- Destruction of adjacent instrumentation and wire bundles
- Penetration of the aluminum wing leading edge spar

Proposed Breach Path and Directionality of Flow



Found September, 2004



Vehicle Assembly Building Today

